FORTSCHRITTE DER PHYSIK

HERAUSGEGEBEN IM AUFTRAGE DER PHYSIKALISCHEN GESELLSCHAFT

IN DER

DEUTSCHEN DEMOKRATISCHEN REPUBLIK

VON RUDOLF RITSCHL UND ROBERT ROMPE

BAND 9 · HEFT 11 · 1961

AKADEMIE-VERLAG · BERLIN

INHALT

Seite

V. S. BARASHENKOV, V. M. MALTSEV: Cross Sections for Elementary Particle Interactions 549

Die „FORTSCHRITTE DER PHYSIK“ sind durch den Buchhandel zu beziehen.

Falls keine Bezugsmöglichkeit durch eine Buchhandlung vorhanden ist, wenden Sie sich bitte

in der Deutschen Demokratischen Republik

an den AKADEMIE-VERLAG, GmbH., Berlin W 8, Leipziger Straße 3—4

in der Deutschen Bundesrepublik

an die Auslieferungsstelle: KUNST UND WISSEN, Inhaber Erich Bieber, Stuttgart S, Wilhelmstraße 4—6

bei Wohnsitz im Ausland

an den Deutschen Buch-Export und -Import, GmbH., Leipzig C 1, Postschließfach 276

oder direkt an den AKADEMIE-VERLAG, GmbH., Berlin W 8, Leipziger Straße 3—4

Fortschritte der Physik 9, 549—611 (1961)

Cross Sections for Elementary Particle Interactions

V. S. Barashenkov, V. M. Maltsev

Joint Institute for Nuclear Research, Dubna (USSR)

Laboratory of Theoretical Physics

Introduction

A great deal of experimental data on the cross sections for elementary particle interaction has been so far accumulated. However, these data are distributed in numerous original papers and reports what makes the use of them very difficult. Besides, in a number of papers the cross sections were determined from relative measurements (e. g., the ratio of the elastic scattering cross section to the total cross section was measured, the value of the latter one has been taken from another paper). The cross sections thus obtained must be renormalized in accordance with the more recent experimental data. In some cases such a renormalization changes considerably the magnitude of the cross sections pointed out in original papers.

At the present time several reviews are available in which the experimental values of the cross sections are gathered: in reviews [*1—3*] are treated the cross sections for proton and neutron interaction with protons; in review [*4*] the total cross section for pion interaction with nucleons; in [*5*] are collected the data on interactions of nucleons, antinucleons, K and π-mesons at high energies $T \geq 0.8$ Bev[1]. However, these reviews are far from being complete. So, after paper [*5*] had been published, we received many letters from experimentalists who specified and supplemented the data they published earlier. There were also obtained new theoretical and experimental results which specify essentially the picture of particle interaction at high energies.

In the following we are going to treat in more detail the experimental data on the cross sections for the interactions of nucleons, antinucleons, K- and π-mesons at different energies. A special emphasis is laid upon the region of high energies. The interactions at these energies have some specific features, common for particles of different kinds. From the analysis of these interactions it is possible to get the information on the phenomena occuring in the region of very small space-time scales.

A majority of experimental data is obtained from the experiments with accelerators where large densities of the particle beams allow to make precision measurements. Only an insignificant part of the data is extracted from the cosmic ray experiments. A comparatively low accuracy is gained in these experiments because of difficulties in measurements. The measured magnitudes are, as a rule, averaged over large energy intervals. However, this small part of the data is of greatest importance since it yields information on particle interaction at gigantic energies of hundreds and thousands Bev. If the 25 Bev accelerator recently starfed up at Geneve makes it possible to penetrate into the matter up to the distance of $\lambda \simeq T_{\max}^{-1/2} \simeq 5 \cdot 10^{-15}$ cm, then the cosmic ray experiments are likely to remain for long the only means of studying the space-time scales: $\lambda \sim 10^{-15} \div 10^{-18}$ cm.

---

[1] Here and everywhere further T will denote the kinetic energy of an incident particle in the lab. system.

As far as the possibilities of high-energy neutrino experiments have been recently discussed intensively (see, e. g., [7] where a detailed bibliography is given), we are going to consider in brief the theoretical data on the cross sections for weak interactions at very high energies.

II. Experimental Data

Different definitions of the interaction cross sections are used in original papers. Therefore, before passing to the consideration of the experimental data we agree on what we shall mean by different kinds of the interaction cross sections and introduce necessary notations.

The total interaction cross section σ_t is composed of the elastic scattering cross section σ_{el} and the cross section for inelastic processes σ_{in}:

$$\sigma_t = \sigma_{el} + \sigma_{in}$$

in its turn

$$\sigma_{el} = \sigma_d + \sigma_p + \sigma_{ie} + \sigma_{dp}.$$

Here σ_d is the cross section for the diffraction scattering. This part of elastic scattering is completely determined by inelastic reactions and vanishes at $\sigma_{in} \to 0$.

σ_p is the cross section for elastic "potential scattering". The Coulomb scattering of two charged particle or scattering of the nucleons which exchange a meson may serve as an example of such scattering. It is essential that the interacting particles preserve their individuality at each moment of time.

In the process of interaction the primary particles may loose their individuality at some moment of time having formed one "compound-particle" which, in the particular case, may decay again into these particles. Such elastic scattering will be characterized by the cross section σ_{ie} where the index i indicates the "inelastic origin" of this scattering. In some cases (e. g., in the course of calculations of the probabilities of the compound-particle decay) it turns out to be necessary to include σ_{ie} into the cross section for inelastic reactions σ_{in}. However, in the following it will always be clear what is meant by the cross sections σ_{el} and σ_{in}.

σ_{dp} is the cross section for scattering which is due to the interference between the diffraction scattering and that part of the potential scattering which is coherent to it. It stands to reason, that elastic scattering via the compound—particle is not coherent with the diffraction scattering.

In some cases one can distinguish such a type of elastic scattering when the nature of particles does not alter as a result of interaction, but the particles change their roles: for instance, in proton-neutron scattering p + n → n + p. Such a scattering may be colled the "scattering with a commutation". Evidently,

$\sigma_{\mathrm{pn}\to\mathrm{np}}(\theta) = \sigma_{\mathrm{pn}\to\mathrm{pn}}(\pi - \theta)$. From the physical point of view at low energies the scattering with a commutation differs in no way from elastic scattering of the "usual type", since the angular distribution $\sigma(\theta)$ is symmetrical with respect to the angle $\theta = \pi/2$. However, at high energies the "usual elastic scattering" is mainly concentrated in the angle region $\theta < \pi/2$, and the elastic scattering with a commutation may be found experimentally [*8*, *9*].

The cross section for inelastic interaction σ_{in} is composed of the cross sections for all possible inelastic channels of the reaction

$$\sigma_{\mathrm{in}} = \sum_j \sigma_{\mathrm{in}}^{(j)}.$$

A particular case of inelastic scattering is "charge exchange elastic scattering" (e. g., $\pi^- + \mathrm{p} \to \pi^0 + \mathrm{n}$), characterized by the cross section σ_{ex}. However, in the following it will be more convenient for us to consider this cross section separately and not to include it into σ_{in} [2]).

Another channel of inelastic scattering is the "spin-flip elastic scattering" with the cross section σ_{s}. If the cross section averaged over the spins of interacting particle is measured experimentally (the unpolarized beam and unpolarized target), then σ_{s} is included automatically into the experimental value of the elastic scattering cross section σ_{el}.

We agree also to use the following short notations of the methods with the aid of which the experimental data are obtained:

H-BC — hydrogen bubble chamber;
D-BC — deuterium bubble chamber;
P-BC — propane bubble chamber;
H-DC — hydrogen diffusion chamber;
D-DC — deuterium diffusion chamber;
IC — ionization chamber;
C — counters;
Em — an analysis of primary particle interactions in the emulsions;
H-Em — the primary particles, scattered on the hydrogen targed, are detected by the emulsion;
Cu — the neutrons scattered on the hydrogen target were detected according to the reaction $\mathrm{Cu}^{63}(\mathrm{n}, 2\mathrm{n})\,\mathrm{Cu}^{62}$;
CC — the neutrons scattered on the hydrogen target were detected according to the reaction $\mathrm{C}^{12}(\mathrm{n}, 2\mathrm{n})\,\mathrm{C}^{11}$;
N — the method of measurements is not indicated.

The errors in the cross section $\delta\sigma_{\mathrm{t}}$ if they are not indicated by the authors, are assumed to be: $\delta\sigma_{\mathrm{t}} = \sqrt{\delta\sigma_{\mathrm{el}}^2 + \delta\sigma_{\mathrm{in}}^2}$. Analogously, we shall calculate the errors of elastic and inelastic cross section $\delta\sigma_{\mathrm{el}}$ and $\delta\sigma_{\mathrm{in}}$ (if experimental errors of two other cross sections are known).

After these general remarks we are proceeding to the consideration of the experimental data.

---

[2]) In many papers σ_{ex} is included into σ_{in} at high energies. However, $\sigma_{\mathrm{ex}} \ll \sigma_{\mathrm{in}}$ and the respective change of σ_{in} is insignificant. At low energies σ_{ex} is large and it is convenient to be considered separately.

2.1. Nucleon-Nucleon Interactions

Tables I—VI present experimental data on the cross sections for NN interactions. At low energies the Coulomb forces affect essentially the proton interaction. Therefore, the cross sections obtained by direct integrating the experimental angular distributions $\sigma_t = \frac{1}{2}\int \sigma(\theta)\, d\Omega$ will considerably differ from the "nuclear cross sections"[3]. It is possible to get more exact values of the cross sections for pp interactions which do not include Coulomb contributions if one takes into account that at low energies the nuclear scattering is isotropic, and the Coulomb forces distort the angular distributions $\sigma(\theta)$ only in the small $\theta < \pi/2$ and large $\theta > \pi/2$ angle regions.

In this case

$$\sigma_{\text{nuclear}}(\theta) \simeq \sigma_{\text{exper}}(90^\circ)$$

$$\sigma_t = \frac{1}{2}\int \sigma_{\text{nuclear}}(\theta)\, d\Omega = 2\pi\, \sigma_{\text{exper}}(90^\circ). \tag{1}$$

Such an approach is justified up to the energies of about 300—400 Mev, since at these energies the experimental angular distributions are indicated to be still isotropic with the exception of small and large angle regions [*3, 10*]. Formula (1) is not applicable for very low energies when the Coulomb scattering takes place at the angles $\theta = \pi/2$ with a noticeable probability.

In Fig. 1 the cross sections calculated by formula (1) are compared with those calculated by the experimental values of the nuclear scattering lengths (in more detail see 3.1). As is seen, in the range of energies $T \simeq (1-20)$ Mev the Coulomb forces increase $\sigma_t(\text{pp})$ appreciably.

Up to the energies of $T = 400$ Mev the majority of the cross sections given in Table 1 have been obtained by formula (1). The same formula was used in calculating the errors $\delta\sigma_t = 2\pi\delta\sigma_{\text{exper}}(90^\circ)$. These errors are underestimated since the errors due to an inaccuracy of (1) are not taken into account.

In some papers the reaction C^{12} (p, pn) C^{11} was employed as an absolute monitor in measuring $\sigma_t(\text{pp})$. As far as at present the values of the cross sections for this reaction are found to be more exact [*11, 12*], then some of the values of $\sigma_t(\text{pp})$ obtained earlier should be renormalized. The renormalized values of the cross sections are indicated in Table I by the sign +.

In some cases the cross section σ_{in} in Table III has been obtained by summing the cross sections for the partial inelastic channels taken from the papers of different authors. At the same time the cross section for $p + p \rightarrow \pi^+ + d$ has been determined in some cases with the aid of the experimental cross section for the inverse reaction $\pi^+ + d \rightarrow p + p$. All the papers used for calculating σ_{in} are listed in references.

In Table I are also given the values of the cross section $\sigma_t(\text{pp}) = \sigma_t(\text{nn})$ obtained by the difference method from the experiments on scattering and absorption of neutrons on deuterium and hydrogen

$$\sigma_t(\text{nn}) = \sigma_t(\text{nd}) - \sigma_t(\text{np}) + I(\text{nd}).$$

By analogy the cross sections for pn interaction shown in Table IV have been calculated:

$$\sigma_t(\text{pn}) = \sigma_t(\text{pd}) - \sigma_t(\text{pp}) + I(\text{pd}).$$

---

[3] The factor 1/2 before the integral takes into acount the identity of the two protons after elastic pp scattering.

The corrections I(nd) and I(pd) are due to the fact that the absorption or scattering of an incident nucleon by the nucleon of a deuterium nucleus decreases if the latter one falls on the shadow of the other nucleon (the screening effect). These corrections have been calculated by GLAUBER's method [*13*] (in more

Table I. pp interaction

T	method	σ_t [mb]	T	method	σ_t [mb]
0	*)	17800 ± 40	44,66	C [*37*]	59,7 ± 0,6
1,855 Mev	C [*14*]	1053 ± 30	50,17	C [*37*]	52,8 ± 0,6
2,425	C [*14*]	985 ± 2	52	C [*42*]	55,5 ± 3,9
3,037	C [*14*]	884 ± 3	56,15	C [*37*]	46,8 ± 0,5
3,435	H-Em [*15*]	835 ± 15	61,92	C [*37*]	42,5 ± 0,4
3,527	C [*14*]	812 ± 2	66	C [*44*]	41,4 ± 4,1
3,899	C [*14*]	757 ± 2	68,3	C [*45*]	38,7 ± 0,4
4,203	C [*14*]	717 ± 2	68,42	C [*37*]	38,5 ± 0,4
4,96	H-Em [*16*]	625 ± 13	69,5	C [*42*]	37,4 ± 2,3
5,07	H-Em [*17*]	602 ± 6	75	C [*46*]	36,4 ± 7,5
5,14	C [*18*]	597 ± 13	78,5	C [*42*]	33,9 ± 2,0
5,77	H-Em [*21*]	548 ± 4	85	CC [*47*]	34,0 ± 3,0^{+}
5,77	C [*21*]	556 ± 5	93,4	C [*48*]	33,0 ± 5,0^{+}
6,848	H-Em [15]	479 ± 9	95	C [*44*]	28,5 ± 1,3
7,03	H-Em [*22*]	414 ± 1	95	C [*42*]	29,2 ± 1,6
7,514	H-Em [*15*]	435 ± 7	95	CC [*49*]	31,0 ± 4,0^{+}
8,0	C [*23*]	377 ± 8	97,2	C [*48*]	32,0 ± 4,0^{+}
9,68	C [*24*, 37]	343 ± 3	98	C [*50*]	27,7 ± 1,3
9,69	C [*26*, *27*]	342 ± 3	105	C [*46*]	30,1 ± 5,7
9,7	C [*28*]	352 ± 3	109	C [*51*]	29,1 ± 3,6^{+}
10	C [*29*]	314 ± 13	117	C [*51*]	27,2 ± 2,4^{+}
12,4	H-Em [*30*]	252 ± 5	118	C [*44*]	25,1 ± 1,3
14,16	C [*31*]	227 ± 3	118	C [*52*]	24,8 ± 0,8
14,5	C [*32*]	210 ± 1	132	C [*51*]	25,3 ± 2,4^{+}
18,2	C [*33*]	171 ± 1	142	C [*50*]	25,2 ± 1,2
18,8	C [*34*]	171 ± 4	144	C [*53*]	20,2 ± 0,7
19,8	C [*35*]	155 ± 2	146	C [54]	22,6 ± 2,5
21,9	C [*34*]	143 ± 3	147	C [*44*]	25,7 ± 1,2
25,2	C [*34*]	117 ± 3	147	C [*55*]	22,4 ± 2,6
25,45	C [*34*]	115 ± 3	149	C [*51*]	24,8 ± 2,0^{+}
25,63	C [*36*]	117 ± 1	153	C [*56*]	24,3 ± 0,2^{+}
28,16	C [*24*]	102 ± 1	155	C [*57*]	23,0 ± 3,1
29,4	H-Em [*38*]	100 ± 3	160	C [*3*]	26,1 ± 1,0
30,14	H-Em [*39*]	94 ± 2	164	C [*52*]	22,6 ± 1,1
31,15	C [*37*]	92 ± 1	169	C [*59*]	23,1 ± 2,0^{+}
31,45	C [*34*]	91 ± 2	169	C [*51*]	23,1 ± 2,0^{+}
31,8	C [*34*]	90 ± 2	170	C [*60*]	23,2 ± 1,9
31,8	C [*40*]	89 ± 2	208	C [*61*]	25,8 ± 2,0
34,2	C [*37*]	84 ± 1	225	C [*62*]	22,4 ± 0,9
36,9	C [*37*]	76 ± 1	240	C [*63*]	22,4 ± 1,8
39,4	C [*41*]	69,2 ± 0,05	240	H-Em [*64*]	22,8 ± 1,8
39,6	C [*37*]	70 ± 1	247	C [*52*]	22,4 ± 1,8
41	C [*42*]	71,6 ± 5,0	260	C [*60*]	22,6 ± 1,3
42	CC [*43*]	86 ± 13^{+}	270	C [*53*]	23,0 ± 2,0

---

*) Calculated by the experimental value of the scattering length (see 3.1).

Table I. (continued)

T	method	σ_t [mb]
270	C [*65*]	19,0 ± 3,0
280	C [*66*]	16,0 ± $4{,}0^{+}$
315	C [*61*]	24,3 ± 1,0
330	C [*62*]	23,4 ± 0,9
345	C [*52*]	23,2 ± 0,3
350	C [*67*]	23,2 ± $0{,}7^{+}$
380	C [*68*]	23,0 ± $1{,}5^{+}$
380	C [*69*]	24,4 ± 0,4
408	C [*70*]	24,0 ± 1,0
410	C [*71*]	28,0 ± $4{,}0^{+}$
410	C [*72*]	$26{,}5^{+1{,}4}_{-1{,}3}$
410	C [*73*]	26,9 ± 0,7
440	C [*74*]	27,0 ± 2,0
460	C [*73*]	27,6 ± 0,4
500	C [*68*]	30,6 ± $2{,}0^{+}$
500	C [*73*]	29,9 ± 0,4
528	C [*84*]	30 ± 7
535	C [*72*]	$29{,}8^{+1{,}3}_{-1{,}4}$
540	C [*73*]	32,1 ± 0,5
560	C [*75, 76*]	34,0 ± 0,5
580	C [*73*]	35,6 ± 0,5
590	C [*68*]	37,8 ± $2{,}1^{+}$
590	C [*74*]	36,0 ± 3,0
600	C [*73*]	36,6 ± 0,5
615	C [*72*]	$37{,}7^{+1{,}4}_{-1{,}0}$
620	C [*73*]	38,6 ± 0,5
630	C [*68*]	42,8 ± $3{,}2^{+}$
640	C [*73*]	39,8 ± 0,6
660	C [*73*]	41,4 ± 0,6
740	C [*72*]	$44{,}4^{+2{,}8}_{-2{,}6}$
747	C [*77*]	$46{,}9^{+1{,}0}_{-0{,}6}$
765	C [*78*]	44,8 ± $3{,}8^{+}$
797	C [*77*]	$47{,}5^{+2{,}2}_{-1{,}1}$
800	C [*74*]	47 ± 2
800	C [*77*]	$47{,}5^{+2{,}2}_{-1{,}1}$
810	H-DC [*79, 80*]	48 ± 4
830	C [*81*]	$47{,}8^{+1{,}6}_{-1{,}2}$
850	C [*81*]	$47{,}6^{+1{,}7}_{-1{,}2}$
910	C [*82*]	46,1 ± 0,5
920	C [*77*]	$47{,}7^{+3{,}0}_{-1{,}1}$
925	Em [*83*]	51 ± 3
940	C [*84*]	49 ± 5
1,0 Bev	C [*74*]	48 ± 3,5
1,03	C [*77*]	$46{,}5^{+2{,}0}_{-0{,}6}$
1,075	C [*81*]	$48{,}3^{+1{,}6}_{-1{,}1}$
1,17	C [*77*]	$46{,}3^{+3{,}2}_{-0{,}8}$
1,275	C [*81*]	$47{,}5^{+1{,}6}_{-1{,}2}$
1,295	C [*81*]	$49{,}4^{+1{,}6}_{-1{,}1}$
1,3	C [*77*]	$45^{+3{,}0}_{-1{,}0}$
1,4	C [*85*]	50,4 ± $1{,}8^{+}$
1,490	C [*81*]	$47{,}2^{+2{,}6}_{-1{,}2}$
1,7	C [*77*]	$45{,}6^{+1{,}9}_{-0{,}7}$
2,0	C [*81*]	$41{,}4^{+3{,}2}_{-1{,}4}$
2,0	H-BC [*455*]	48,5 ± 1,7
2,17	C [*77*]	$45{,}1^{+0{,}9}_{-0{,}5}$
2,6	C [*3, 86*]	$41{,}6^{+4}_{-1{,}6}$
2,75	C [*77*]	$43{,}3^{+0{,}6}_{-0{,}5}$
3,0	Em [*87*]	44,5 ± 2,0
3,0	Em [*88*]	42,5
3,17	C [*77*]	42,4 ± 0,6
4,14	C [*89*]	43,7 ± 0,7
5,13	C [*89*]	43,7 ± 0,4
5,3	H-DC [*90*]	32,4 ± 6
6,12	C [*89*]	43,3 ± 0,4
6,2	Em [*91*]	31,4
9	Em [*92*]	31 ± 7,6
9	C [*93*]	39,4 ± 1,5
9,14	C [*89*]	42,1 ± 0,4
9,8	C [*89*]	40,1 ± 0,6
11,5	C [*93*]	39,0 ± 1,5
14,9	C [*93*]	38,7 ± 1,5
16,8	C [*93*]	39,7 ± 1,5
18,5	C [*93*]	39,7 ± 1,5
20,5	C [*93*]	39,4 ± 1,5
22,6	Em [*25*]	42,5 ± 1,4
23,3	C [*93*]	38,7 ± 1,5
27,5	C [*93*]	39,9 ± 1,5

Table II. pp interaction

T	method	σ_{el} [mb]	T	method	σ_{el} [mb]
Below the threshold for π°-meson production $T \leq 290$ Mev $\sigma_{el} = \sigma_t$			1,0 Bev	C [*74*]	$19{,}2\ {}^{+\,3}_{-\,2}$
417 Mev	C [*95*]	21,5 ± 0,8	1,0	C [*103*]	20,8 ± 1,0
429	C [*53*]	21,5 ± 1,9	1,0	C [*104*]	20,7 ± 1,2
435	H-Em [*96*]	22,2 ± 1,1	1,5	H-DC [*80, 105*]	20 ± 2
437	C [*97*]	23,8 ± 1,2	2,0	H-BC [*455*]	18,7 ± 1,3
440	C [*74*]	23,5 ± 1,2	2,24	C [*86*]	16,9 ± 2,5
460	C [*75, 76*]	24,0 ± 0,6	2,75	H-DC [*80, 107*]	16 ± 2
528	C [*84*]	24 ± 5	2,85	H-BC [*109*]	17,3 ± 1,5
560	C [*75, 76*]	25,2 ± 0,8	2,9	Em [*108*]	12,5 ± 2,5
582	P-BC [*98*]	24,2 ± 1,6	3,0	Em [*87*]	8,9 ± 1,0
590	C [*74*]	25,0 ± 2,0	4,4	C [*86*]	9,0 ± 1,4
650	H-DC [*99*]	26,3 ± 1,8	5,3	H-DC [*90*]	5,6 ± 2,3
660	C [*75, 76*]	24,7 ± 1,0	5,7	Em [*110*]	13 ± 6
800	C [*3, 74*]	21,5 ± 2,0	6,15	C [*86*]	6,9 ± 1,0
810	H-DC [*79, 80*]	24 ± 2	6,2	Em [*91*]	8,8 ± 2
925	Em [*83*]	17 ± 3	6,2	N [*111*]	8
930	P-BC [*100*]	21,6 ± 2,5	8,2	Em [*112*]	8,74 ± 0,4
940	C [*84*]	26 ± 3	9	Em [*92*]	10 ± 3
970	H-DC [*101*]	25,8 ± 0,9	22,6	Em [*25*]	$5{,}5\ {}^{+\,3{,}9}_{-\,2{,}8}$
970	D-DC [*102*]	25,9 ± 1,7			

Table III. pp interaction

T	method	σ_{in} [mb]	T	method	σ_{in} [mb]
Below the threshold for π°-meson production $T \leq 290$ Mev $\sigma_{in} = 0$			620	C [*73*]	13,6 ± 1,1
340 Mev	C [*113, 115*]	0,55 ± 0,12	633	C [*113, 118, 120*]	14,81 ± 0,87
345	C [*113, 114, 116*]	0,67 ± 0,13	640	C [*73*]	14,8 ± 1,2
380	C [*113, 114, 116*]	1,85 ± 0,35	650	H-DC [*99*]	14,4 ± 1,4
410	C [*73*]	2,9 ± 0,9	650	C [*113, 118, 120*]	16,0 ± 0,88
437	C [*117*]	2,43 ± 0,34	657	C [*113, 118, 120*]	17,22 ± 0,87
440	C [*74*]	3,5 ± 2,3	660	C [*73*]	16,7 ± 1,2
460	C [*73*]	3,6 ± 0,7	800	C [*3, 74*]	25,5 ± 2,8
485	C [*113, 118, 119*]	3,84 ± 0,56	810	H-DC [*79, 80*]	24 ± 2
500	C [*73*]	4,9 ± 1,1	925	Em [*83*]	34 ± 5,5
510	C [*113, 118, 120*]	5,94 ± 0,70	940	C [*84*]	23 ± 3
520	C [*113, 118, 119*]	5,98 ± 0,68	970	H-DC [*101*]	20,9 ± 1,3
528	C [*84*]	6 ± 3	970	D-DC [*102*]	18,7 ± 1,5
540	C [*73*]	7,1 ± 1,1	1,0 Bev	C [*74*]	28,8 ± 3,2
560	C [*75, 76*]	8,8 ± 0,9	1,5	H-DC [*80, 105*]	27 ± 3
560	C [*113, 118,* 120]	8,38 ± 0,68	2,0	H-BC [*455*]	29,8 ± 2,1
580	C [*73*]	10,6 ± 1,1	2,75	H-DC [*80, 107*]	26 ± 3
584	C [*113, 118, 121*]	10,3 ± 0,8	3,0	Em [*87*]	35,6 ± 4
590	C [*74*]	10,8 ± 3,6	5,3	H-DC [*90*]	26,8 ± 5,5
597	C [*113, 118, 120*]	11,39 ± 0,85	6,2	Em [*91*]	22,6 ± 5,3
600	C [*73*]	11,6 ± 1,1	6,2	Em [*122*]	$23\ {}^{+\,7}_{-\,6}$
610	C [*113, 118, 120*]	12,38 ± 0,85	9	Em [*92*]	21 ± 7
620	C [*113, 118, 120*]	13,54 ± 0,90	22,6	Em [*25*]	37 ± 11

Table IV. np interaction

T	method	σ_t [barn]	*T*	method	σ_t [bm]
0 ev	*)	20,57 ± 0,04	19,6	IC [*128*]	520 ± 90
1,0	C [*123*]	21,0 ± 0,2	19,66	C [*135*]	494 ± 2,5
15	C [*123*]	19,8 ± 0,1	19,93	C [*136*]	504 ± 10
17	C [*123*]	20,3 ± 0,1	21,10	IC [*128*]	410 ± 90
20	C [*123*]	20,1 ± 0,1	25	CC [*137*]	390 ± 30
24	C [*123*]	20,0 ± 0,1	27,2	C [*138*]	360 ± 30
28	C [*123*]	20,8 ± 0,1	38,0	C [*139*]	223,0 ± 7,6
35	C [*123*]	20,6 ± 0,1	39,0	C [*140*]	223,0 ± 7,6
45	C [*123*]	20,4 ± 0,1	42,0	CC [*141*]	203 ± 7
58	C [*123*]	19,5 ± 0,1	42,0	C [*142*]	170,0 ± 8,3
67	C [*123*]	22,3 ± 0,4	47,5	C [*143*]	196 ± 10
79	C [*123*]	20,1 ± 0,4	63	C [*139*]	126 ± 3
94	C [*123*]	20,7 ± 0,3	64,5	C [*140*]	126 ± 3
110	C [*123*]	20,3 ± 0,2	85	CC [*144*]	83 ± 4
140	C [*123*]	19,8 ± 0,3	88	C [*143*]	86,1 ± 2,0
180	C [*123*]	18,7 ± 0,2	90	IC [*145*]	93,0 ± 7,0
230	C [*123*]	20,8 ± 0,4	90,0	C [*142*]	76,0 ± 1,7
300	C [*123*]	20,2 ± 0,4	93,4	C [*146*]	77,0 ± 5,0
430	C [*123*]	19,3 ± 0,3	95	C [*139*]	73,9 ± 3,0
660	C [*123*]	20,8 ± 0,3	95	C [*147*]	73,0 ± 1,5
1,1 kev	C [*123*]	19,5 ± 0,3	97	C [*140*]	73,9 ± 3,0
1,9	C [*123*]	19,5 ± 0,3	97,0	C [*148*]	74,0 ± 10,0
10	C [*123*]	16,0 ± 0,2	97,2	C [*146*]	76,0 ± 3,0
100	C [*123*]	10,5 ± 0,2	101,1	C [*146*]	80,0 ± 7,0
1,005 Mev	C [*124*]	4,228 ± 0,018	106,8	C [*146*]	59,0 ± 16,0
1,315	C [*125*]	3,675 ± 0,020	117	C [*148*]	61,5 ± 8,6
2,54	C [*124*]	2,525 ± 0,009	126	C [*139*]	56,9 ± 1,8
4,75	C [*126*]	1,69 ± 0,006	140	C [*148*]	48,5 ± 5,6
7,17	C [*127*]	1,24 ± 0,020	153	C [*139*]	46,4 ± 1,2
8,77	C [*127*]	1,04 ± 0,010	156	C [*140*]	46,4 ± 1,2
9,30	IC [*128*]	920 ± 80mb	156	C [*148*]	50,5 ± 8,3
10,42	C [*127*]	940 ± 20	160	C [*149*]	51,2 ± 2,6
10,60	IC [*128*]	780 ± 90	169	C [*150*]	49,2 ± 1,6
11,13	C [*127*]	880 ± 20	180	C [*148*]	44,0 ± 12,0
12,50	C [*129*]	690 ± 10	208	C [*151*]	37,0 ± 2,0†
12,80	IC [*128*]	830 ± 90	220	C [*148*]	41,3 ± 3,5
13,13	C [*127*]	760 ± 20	220	C [*149*]	41,0 ± 4,0
13,50	C [*129*]	694 ± 19	260	C [*152*]	35,0 ± 8,8
13,90	C [*130*]	770 ± 40	270	C [*153*]	38,0 ± 1,5
14	Cu [*131*]	700 ± 60	280	C [*154*]	33,0 ± 3,0
14	C [*132*]	690 ± 60	315	C [*151*]	32,5 ± 4,0†
14,02	C [*127*]	720 ± 10	350	C [*155*]	35,6 ± 0,7
14,10	C [*133*]	689 ± 5	380	C [*156*]	34,0 ± 2,0
14,12	C [*134*]	686 ± 7	380	C [*157*]	$31{,}0\,^{+1{,}5}_{-1{,}3}$†
14,20	Cu [*3*]	675 ± 20			
14,80	IC [*128*]	610 ± 90	408	C [*158*]	31,6 ± 2,0†
15	Cu [*131*]	660 ± 70	410	C [*159*]	33,7 ± 1,3
16,5	IC [*128*]	660 ± 100	500	C [*156*]	35,0 ± 2,0
18,10	IC [*128*]	550 ± 80	590	C [*156*]	36,0 ± 2,0

---

*) Calculated by the experimental values of the scattering lengths [see 3.1).

Table IV. (continued)

T	method	σ_t [barn]	T	method	σ_t barn]
590	C [*157*]	$36{,}2\,{}^{+\,2{,}2}_{-\,2{,}0}$†	1,4	C [*85*]	42,4 ± 1,8
			1,48	C [*81*]	40,8 ± 1,9†
630	C [*156*]	37,0 ± 4,0	2,0	C [*81*]	40,9 ± 1,9†
765	C [*160*]	34,4 ± 1,6	2,6	C [*81*]	37,4 ± 1,8†
810	C [*81*]	32,5 ± 1,2†	4,5	C [*161*]	33,6 ± 1,6
910	C [*82*]	39,2 ± 3,1†	8,5	Em [*9*]	> (30 ÷ 32)**
970	D-DC [*102*]	37,5 ± 3,7†	9	C [*93*]	42 ± 2,9†
1,06 Bev	C [*81*]	34,0 ± 2,0†	14,9	C [*93*]	42,1 ± 2,3†
1,26	C [*81*]	38,8 ± 1,4†	23,2	C [*93*]	41,4 ± 2,3†

**) When determining this value in [*9*] some assumptions have been made, the validity of which is far from being evident.

Table V. np interaction

T	method	σ_{el} [mb]	σ_{in} [mb]
Below the threshold for π^0-meson production $\sigma_{el} = \sigma_t$ and $\sigma_{in} = 0$			$T \leq 290$ Mev
300 Mev	IC [*162*]	—	~0,08
380	C [*156*]	~33	~1
400	H-Em [*163*]; C [*164*]	—	0,72 ± 0,10
440	C [*164, 156*]	—	1,35 ± 0,3
485	C [*164, 156*]	—	3,00 ± 0,70
520	C [*164, 156*]	—	4,4 ± 1,0
560	C [*164, 156*]	—	5,21 ± 0,85
590	C [*164, 166*]	—	5,8 ± 0,5
597	C [*164, 165*]	—	8,9 ± 1,0
610	C [*164, 165*]	—	10,1 ± 1,4
620	C [*164*, 165]	—	10,8 ± 1,5
630	C [*164, 165*]	—	11,7 ± 1,0
630	C [*167*]	26,0±4,5	—
645	C [*164, 165*]	—	11,8 ± 1,5
660	C [*164, 165*]	—	10,5 ± 2,4
665	C [*164, 165*]	—	11,3 ± 1,4
970	D-DC [*102*]	16,2±3,5	21,3 ± 3

detail see Appendix I). Their values is not determined very exactly. Therefore, the values of σ_t(nn) and σ_t(pn) given in the Tables should be considered as approximate. Here the errors in $\delta\sigma_t$ are purely statistical and smaller than the real ones. For energies of $T \gtrsim 1$ Bev the magnitude of screening corrections makes up about 15—20%. At lower energies their magnitude decreases; below the threshold for inelastic reactions the screening corrections may be neglected. All the cross sections obtained by the difference method from the experiments with deuterium are indicated in the Tables by the sign †.

In Table VI are shown the values of σ_t and σ_{in}, the average ones for pp and pn interactions, obtained by analysing (within the framework of the optical model) the experimental values of the proton mean free paths in emulsions and the experimental values of the proton interaction with nuclei. (In more detail see Appendix II.) The errors $\delta\sigma$ given in the Table correspond to the statistical errors in the values of the mean free path and of the cross sections for proton interaction with nuclei4).

Table VI. pN interaction

T [Bev]		L [cm] m. f. path in emulsion*)	σ_{in} [mb]	σ_t [mb]
Energy interval	Mean energy			
—	4,5 [*168*]	—	—	35 ± 3
—	5,7 [*110*]	$37,6 \pm 5,3$	—	29^{+16}_{-7}
—	5,7 [*169*]	$35,6 \pm 2,4$	—	34^{+11}_{-5}
—	6,2 [*170*]	$34,7 \pm 3,4$	—	$35^{+13,5}_{-6,5}$
—	6,2 [*171, 172*]	$\gtrsim 36,4$	—	$\lesssim 31$
—	6,2 [*122*]	$38,2 \pm 1,5$	—	28 ± 3
—	9 [*92*]	$37,3 \pm 0,7$**)	—	30 ± 2
—	9 [*173*]	$35,7 \pm 0,7$	—	33 ± 2
>9	20 [*174*]	—	—	32 ± 10
—	22,6 [*25*]	$36,6 \pm 1$	—	31^{+3}_{-2}
$0,9 \div 34$	20 [*175*]	—	—	32 ± 3
$28 \div 58$	37 [*176*]	—	28 ± 4	—
$58 \div 121$	77 [*176*]	—	$21 + 4$	—
$121 \div 387$	178 [*176*]	—	25^{+18}_{-7}	—
—	200 [*177*]	42 ± 10	—	22^{+24}_{-13}
—	250 [*58*]	41 ± 10	—	24^{+26}_{-9}

---

*) As comparative calculations have shown, the mean free paths in the emulsion of the NIKFI-P and Ilford G-5 types are practically not different (see Appendix in more detail).

**) The statistical error indicated in [*92*] ($\delta L = 0.3$) is incorrect by a misunderstanding. We are grateful to M. I. PODGORETSKY who drew our attention to this inaccuracy.

The average energy of the three last intervals has been calculated with acount of the energy spectrum of protons in the atmosphere.

As one can see, in the energy range 1—10 Bev the values of $\sigma(pN)$ thus obtained yield an underestimated value for the cross sections $\sigma(pp)$ and $\sigma(pn)$4). However,

---

4) In the papers cited in Table VI, the systematic errors due to a possible missing of stars in scanning the emulsions are not undicated. The account of these errors increases the values of $\sigma_t(pN)$ in Table IV.

A study of the measurement accuracy in emulsions recently undertaken at our Institute by B. P. BANNIK and V. G. GRISHIN has shown that by employing usual methods of measurements the systematic error in δL is, on the average, about two centemeters.

We are grateful to M. J. PODGORETSKY for detailed discussions of these problems.

in cosmic ray experiments at $T \gg 10$ Bev the measurement of the m. f. path L is often the only means for obtaining the information about the magnitude of the cross sections.

The main experimental data are summarized in Figs. 1—3.

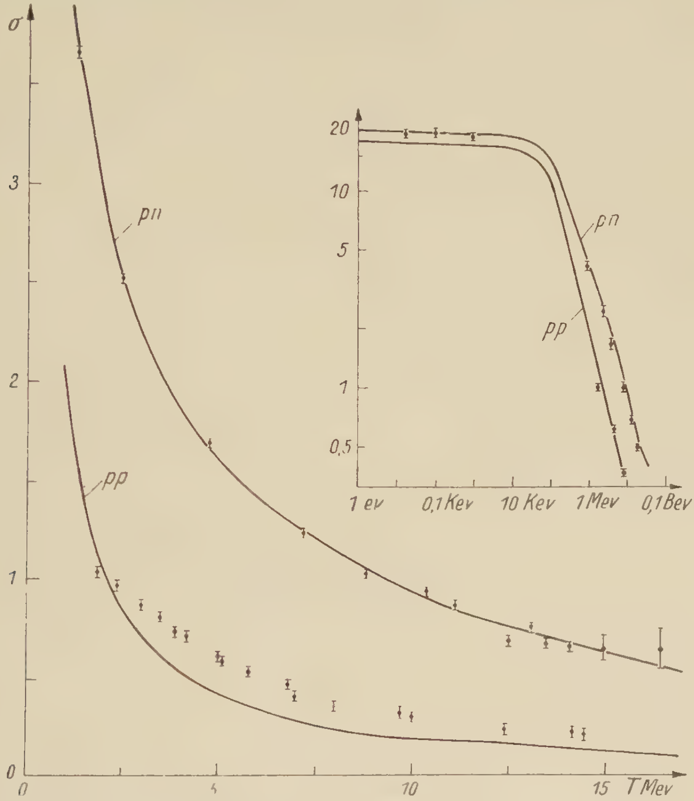

Fig. 1. Cross sections for nucleon interaction at very low energies. Solid curves show the values calculated by the effective range approximation (see 3.1). All the cross sections are given in the units of 10^{-24} cm^2.

The charge symmetry and invariance considerations with respect to the charge conjugation lead to

$$\sigma(\mathrm{pp}) = \sigma(\mathrm{nn}) = \sigma(\overline{\mathrm{p}}\overline{\mathrm{p}}) = \sigma(\overline{\mathrm{n}}\overline{\mathrm{n}})$$

$$\sigma(\mathrm{pn}) = \sigma(\overline{\mathrm{p}}\overline{\mathrm{n}})$$

irrespective of what cross section σ_{t}, σ_{in} or σ_{el} it is[5]).

---

[5]) It is clear that we neglect the electromagnetic interactions what is not, of course, correct for extreme peripheral collisions leading to small-angle scattering. However, these collisions give a very small contribution to the cross sections σ_{t}, σ_{in}, σ_{el}.
The above-mentioned identities of the cross sections remain also valid for the differential elastic scattering cross sections $\sigma(\theta)$.

It is seen from the given experimental data that with the energy increase the cross sections for pp interactions are tending to the constant values. It was very recently thought that the limiting value of $\sigma_t \simeq 30$ mb. However, the experiments carried out at the 25 Bev accelerator at Geneve have shown that this calue should be increased by 10 mb [*8*, *9*]. The limiting values of the cross sections σ_{el} and σ_{in} are equal approximately to (8—9) mb and (30—32) mb, respectively.

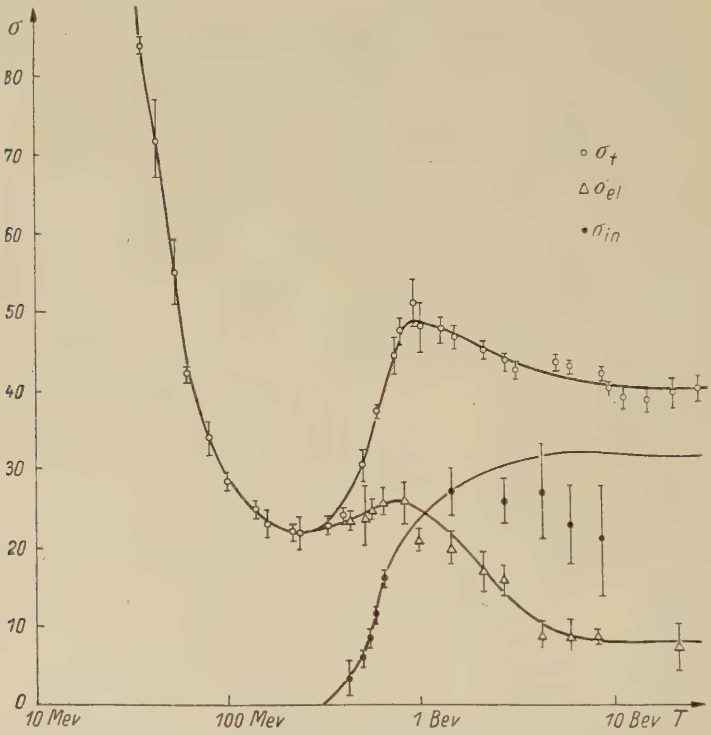

Fig. 2. Cross sections for proton-proton interactions. The values of σ are given in the units of 10^{-27} cm^2.

The cosmic ray experiments show that within the experimental error the cross sections remain constant up to the energies of some hundred Bev. An analysis of the experimental data on wide atmopheric showers point out that the order of the magnitude of the cross section σ_t does not appreciably change, very likely, up to the energies $T \sim 10^9$ Bev. However, the accuracy in cosmic ray experiments is not high, and this conclusion is not a strict one[6]).

The experimental information on np interaction is very poor at high energies. However, one can see from the Tables I—VI and from Figs. 2—3, that with energy the cross section $\sigma_t(np)$ is getting equal to $\sigma_t(pp)$ by its magnitude. Recent measurements [*93*], carried out at Geneve, show that at $T \gtrsim 10$ Bev the experimental value of the Glauber correction is

---

[6]) We are grateful to S. PERNEGER, B. SHIMAK and other workers of the cosmic ray group in Prague for a detailed discussion of these problems and valuable remarks.

$$I = \sigma_t(\mathrm{pp}) - \sigma_t(\mathrm{pn}) \simeq (5 \pm 2)\ \mathrm{mb}.$$

and independent of energy.

It can be expected that at high energies the elastic and inelastic interaction cross section of nucleons are also equal to each other:

$$\sigma_{\mathrm{el}}(\mathrm{pp}) = \sigma_{\mathrm{el}}(\mathrm{pn}); \quad \sigma_{\mathrm{in}}(\mathrm{pp}) = \sigma_{\mathrm{in}}(\mathrm{pn}).$$

The measurements made by BRENER and WILLIAMS [*176*] have shown that in the energy range from 28 up 387 Bev the cross sections for inelastic proton and neutron interaction with Fe nuclei are not distinguished within the experimental error (~30%) what predict the equality between the cross sections for inelastic pp and np interactions at these energies.

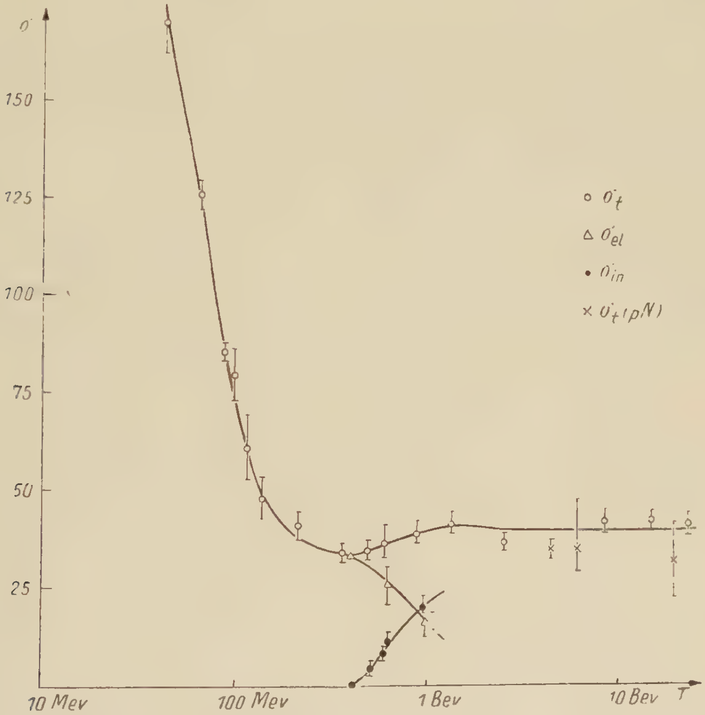

Fig. 3. Cross sections for proton-neutron interactions. The values of $\sigma_t(\mathrm{pN})$ calculated according to the optical theory are indicated.
All the cross sections are given in the units of 10^{-27} cm^2.

2.2. Antinucleon-Nucleon Interactions

The experimental data on antinucleon-nucleon interactions are poorer than on NN interactions and restricted to the energy region $T < 10$ Bev. In the range of low energies the experimental errors are large. The values of the cross sections for $\overline{\mathrm{p}}\mathrm{p}$ and $\overline{\mathrm{p}}\mathrm{n}$ interactions available now are listed in Tables VII, VIII and on

Fig. 4. In some cases, the given cross sections are averaged over wide energy ranges. The magnitude of these intervals is indicated in parentheses. In each of these cases the "average antiproton energy" is also shown, which does not always coincides with the "average energy of the interval".

Table VII. $\bar{p}p$ interaction

T	method	σ_{el} [mb]	σ_{ex} [mb]	σ_{in} [mb]	σ_t [mb]
50 (5 ÷ 80) Mev	H-BC [*178*]	96 ± 43	—	—	210 ± 70
106 (75 ÷ 137)	P-BC [*179*]	66 ± 17	≤ 15	112 ± 23	$\leq 193 \pm 40$
120	P-BC [*180*]	$> 41^{+10\,*)}_{-7}$	—	—	—
133	C [*181*]	72^{+9}_{-11}	10^{+2}_{-3}	84^{+14}_{-12}	166 ± 8
137 (75 ÷ 200)	P-BC [*179*]	$> 62 \pm 12$*)	—	—	—
127 (20 ÷ 235)	Em [*182*]	$> 58^{+40\,*)}_{-17}$	—	—	—
125 (0 ÷ 250)	Em [*183*]	77 ± 17	—	—	—
140 (30 ÷ 250)	Em [*184*]	$70{,}9 \pm 12{,}7$	—	—	—
150 (20 ÷ 230)	Em [*185*]	71^{+30}_{-11}	—	$\leq 86^{+58}_{-37}$	—
150 (50 ÷ 250)	Em [*186*]	71 ± 13	—	—	—
170 (37,5 ÷ 200)	P-BC [*179*]	56 ± 14	—	60 ± 18	—
190	C [*187*]	—	—	—	135 ± 16
197	C [*181*]	64^{+7}_{-9}	11^{+2}_{-4}	77^{+12}_{-10}	152 ± 7
265	C [*181*]	50^{+6}_{-7}	8^{+2}_{-3}	66^{+10}_{-9}	124 ± 7
300	C [*187*]	—	—	—	104 ± 14
333	C [*181*]	49^{+5}_{-7}	7 ± 2	58^{+8}_{-7}	114 ± 4
440	C [*188*]	—	$3{,}0 \pm 1{,}6$	—	—
457	C [*189*]	—	—	$\geq 89 \pm 7$	104 ± 8
460	C [*190*]	—	—	89 ± 8	—
470	P-BC [*451*]	—	—	52 ± 10	—
500	C [*187*]	—	—	—	97 ± 4
534	C [*191*]	44 ± 6	6 ± 2	69 ± 5	119 ± 6
540	C [*190*]	43 ± 5	—	69 ± 4	117 ± 5
700	C [*187*]	—	—	—	94 ± 4
700	C [*190*]	41 ± 4	—	65 ± 4	116 ± 5
700	C [*191*]	43 ± 5	8 ± 2	63 ± 4	114 ± 5
816	C [*191*]	37 ± 5	7 ± 2	60 ± 5	105 ± 6
820	C [*190*]	37 ± 4	—	61 ± 4	108 ± 5
940	H-BC [*454*]	—	$< 7{,}9 \pm 0{,}5$	—	—
948	C [*191*]	33 ± 3	8 ± 2	56 ± 3	96 ± 3
960	C [*190*]	33 ± 4	—	$55 \pm 2{,}5$	96 ± 4
1,0 Bev	C [*192*]	33 ± 2	$5 \pm^{1{,}0}_{1{,}5}$	62 ± 2	100 ± 3
1,068	C [*191*]	30 ± 3	7 ± 1	58 ± 3	96 ± 4
1,07	C [*190*]	30 ± 3	—	60 ± 3	96 ± 4

---

*) The small angle contribution is not taken into account.

Table VII. (continued)

T	method	$\sigma_{\rm el}$ [mb]	$\sigma_{\rm ex}$ [mb]	$\sigma_{\rm in}$ [mb]	$\sigma_{\rm t}$ [mb]
1,25	C [*192*]	28 ± 2	4 ± 1	57 ± 3	89 ± 4
1,67	C [*194*]	—	—	—	100 ± 3
2,00	C [*192*]	25 ± 4	6^{+2}_{-3}	49 ± 3	80 ± 6
2,75	C [*194*]	—	—	—	80 ± 6
4,14	C [*89*]	—	—	—	$67{,}0 \pm 2{,}1$
5,13	C [*89*]	—	—	—	$60{,}6 \pm 2{,}0$
6,12	C [*89*]	—	—	—	$63{,}0 \pm 2{,}3$
9,14	C [*89*]	—	—	—	$46{,}0 \pm 2{,}0$
9,30	C [*89*]	—	—	—	$52{,}6 \pm 2{,}7$
9,8	C [*89*]	—	—	—	$53{,}0 \pm 1{,}1$

All the cross sections for $\bar{\rm p}$n interactions presented in Table VII have been obtained by the difference method from the experiments with deuterium and hydrogen

$$\sigma(\bar{\rm p}{\rm n}) = \sigma(\bar{\rm p}{\rm d}) - \sigma(\bar{\rm p}{\rm p}) + I(\bar{\rm p}{\rm d})$$

where $I(\bar{\rm p}{\rm d})$ is the correction for nucleon screening in deuteron nucleus. Table VIII gives the values of the cross sections with account of this correction calculated by the Glauber method (see Appendix I). All the cross sections obtained by this way are indicated in the Table by the sign †.

Table VIII. $\bar{\rm p}$n interaction

T	method	$\sigma_{\rm el}$ [mb]	$\sigma_{\rm in}$ [mb]	$\sigma_{\rm t}$ [mb]
457 Mev	C [*189*]	—	≥ 74†	113†
460	C [*190*]	—	74 ± 9†	—
540	C [*190*]	$39 + 9$†	80 ± 5†	120 ± 8†
700	C [*190*]	24 ± 9†	71 ± 6†	96 ± 6†
820	C [*190*]	43 ± 10†	69 ± 5†	112 ± 7†
900	C [*193*]	—	64 ± 6†	—
960	C [*190*]	39 ± 8†	64 ± 4†	102 ± 6†
1.07 Bev	C [*190*]	43 ± 6†	66 ± 5†	110 ± 5†

As we see, at high energies the cross sections for $\bar{\rm p}$p and $\bar{\rm p}$n interactions are little different within the experimental error what points to a weak dependence of these interactions on the isotopic spin.

The values of $\sigma_{\rm in}$ presented in the Tables are the sum of the annihilation cross sections $({\rm N} + \bar{\rm N} \rightarrow$ pions + K-mesons) and of the cross section for inelastic scattering without the annihilation $\sigma_{\rm na}({\rm N} + \bar{\rm N} \rightarrow {\rm N} + \bar{\rm N} +$ the particles of other kinds). The cross section $\sigma_{\rm na}$ is zero at low energies, but with increasing energy it is getting larger quickly. The magnitudes of the ratio $\sigma_{\rm na}/\sigma_{\rm in}$ for $\bar{\rm p}$p and $\bar{\rm p}$n interactions are strongly different. So, for $\bar{\rm p}$p interaction at $T = 925$ Mev $\sigma_{\rm na}/\sigma_{\rm in} = 0.09 \pm 0.02$ [*439*], where as for $\bar{\rm p}$n interaction at $T - 900$ Mev $\sigma_{\rm na}/\sigma_{\rm in} = 0.33 \pm 0.17$ [*440*].

According to the charge symmetry considerations the equalities

$$\sigma(\bar{\mathrm{p}}\mathrm{p}) = \sigma(\bar{\mathrm{n}}\mathrm{n})$$

$$\sigma(\bar{\mathrm{p}}\mathrm{n}) = \sigma(\bar{\mathrm{n}}\mathrm{p})$$

are fulfilled for all the cross sections indicated in the Tables.

One can see from the above data that at $T < 10$ Bev the cross sections for $\bar{\mathrm{N}}\mathrm{N}$ interactions exceed considerably the cross sections for NN interactions. This may be illustrated by the following considerations:

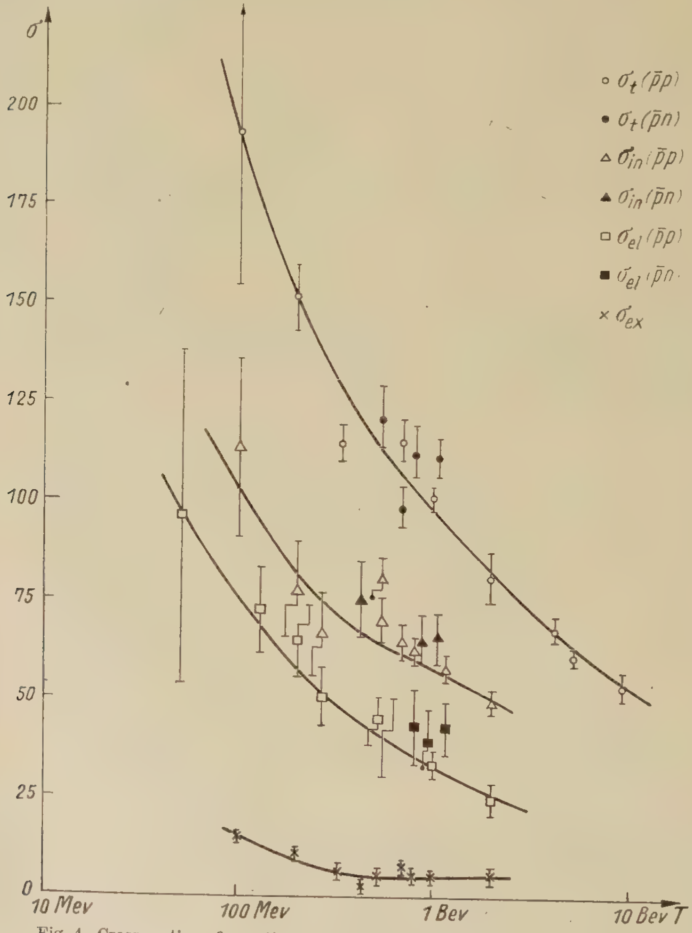

Fig. 4. Cross sections for antiproton interactions with protons and neutrons. The values of σ are given in the units of 10^{-27} cm^2.

As far as an antinucleon is alike a nucleon in many respects, it can like the nucleon be imagined as consisting of a dense core and a comparatively "friable" meson shell. From the point of view of such a model it is quite natural to assume the annihilation to occur in the collision of the nucleon core and the antinucleon. Such collisions will be characterized by strong absorption, and, therefore, by a larger cross section than for N N interactions. In the collision of the cores with the peripheral meson cloud, just as in case of N N collisions, there occurs elastic or inelastic scattering of a nucleon and an antinucleon which is accompanied by the productoin of new particles. In the energy region not exceeding some hundred Mev, such a model of $\bar{\mathrm{N}}\mathrm{N}$ collisions corresponds to the interaction potential differing at $r > 2a$ ($a \simeq \hbar/Mc \simeq 2 \cdot 10^{14}$ cm is a characteristic dimension of a core) only in sign from the known N N potential of Gartenhaus, Signell and Marshak [*441*][7]), while at small distances $r \leq a$ it is characterized by strong absorption. As Koba and Takeda's estimates [*442*], and more exact calculations of Ball, Chew et al [*442*] have shown, the experimental data on $\bar{\mathrm{N}}\mathrm{N}$ interactions are well accounted for by such a phenomenological theory. The corresponding calculations for N N interactions show that in this case a partial compensation of different terms takes place, and the magnitude of the cross sections decreases.

For high energy region there is yet no theory which would allow to calculate the cross sections for nucleon and antinucleon interaction. However, it should be expected that with energy the cross sections for $\bar{\mathrm{N}}\mathrm{N}$ and N N interactions will be comparable (cf. 3.3). Recent measurements made at Geneve [*89*] have shown actually that the difference between the cross sections for $\bar{p}p$ and pp interactions decreases with energy: at $T = 1$ Bev this difference is approximately 45 mb, while at $T = 10$ Bev — already only about 10 mb.

2.3. Interaction of Pions with Nucleons

The experimental values of the cross sections for πN interactions are presented in Tables IX—XIV.

In some papers (e. g., [*208, 215*] and in other) the cross sections are given which are obtained at the same energy be means of the counters: by knocking out the particles from the beam and by integrating the angular distribution. For these cases the mean values

$$\sigma = \frac{\sigma_1 \cdot (\delta\sigma_2)^2 + \sigma_2 \cdot (\delta\sigma_1)^2}{(\delta\sigma_1)^2 + (\delta\sigma_2)^2}; \quad \delta\sigma = \frac{\delta\sigma_1 \cdot \delta\sigma_2}{\sqrt{(\delta\sigma_1)^2 + (\delta\sigma_2)^2}}$$

are given in our Tables. At low energies the corrections for the Coulomb scattering were taken into account [*4*]. At high energies the influence of the Coulomb scattering is insignificant.

In some experimental papers the cross sections σ_{el}, σ_{in} and σ_{ex} were normalized to the value σ_t, taken from another paper. When this value is strongly different from those obtained in more recent papers the cross sections σ_{el}, σ_{in} and σ_{ex} were renormalized.

It should be also emphasized that the value of the cross sections σ_{in} and σ_{ex} listed in Tables X and XI may turn out to be not very exact in the energy range of about 1 Bev, since in the corresponding experimental papers the cases of elastic scattering with a charge exchange were not distinguished out of all the π^- p

---

[7] Let us remind that the pion charges of a nucleon and antinucleon differ in sign. Therefore, in exchanging an odd number of pions, the signs of the N N and $\bar{\mathrm{N}}\mathrm{N}$ interaction potentials are also different in sign.

Table IX. π^-p interaction

T	method	σ_t [mb]	T	method	σ_t [mb]
0	*)	5,8 ± 0,2	215,4	C [*224*]	55,6 ± 1,0
20,7 Mev	C [*456*]	5,4 ± 0,4	216	C [*220, 4*]	57,9 ± 2,5
31,0	C [*456*]	6,5 ± 0,5	217	C [*228, 4*]	57,7 ± 6,0
37	C [*202*]	12,9 ± 1,7	217	C [*212, 4*]	58 ± 6
41,5	C [*204*]	7,8 ± 0,7	220	C [*228*]	52,1 ± 2,3
58	C [*205*]	17,6 ± 2,2	220	C [*229, 4*]	53,6 ± 1,3
65	C [*206*]	15,3 ± 1,6	220,2	C [*224*]	52,2 ± 1,0
72	C [*208*]	15 ± 8	224	H-BC [*230*]	50,5 ± 2,1
79	C [*208*]	20 ± 8	225	C [*224*]	50,2 ± 0,9
85	C [*210*]	13,3 ± 1,1	226	C [*220, 4*]	54 ± 2
89	C [*212*]	21 ± 8	228,3	C [*224*]	48,2 ± 0,9
98	C [*213*]	21,2 ± 0,7	230	N [*433*]	58 ± 9
109	C [*208, 4*]	30 ± 9	231,9	C [*224*]	49,0 ± 0,9
112	C [*212, 4*]	30 ± 9	234,9	C [*224*]	44,5 ± 0,9
120	C [*215, 4*]	32,3 ± 3,0	236	C [*223, 4*]	46,5 ± 2,0
127	C [*208, 4*]	44 ± 10	238,2	C [*224*]	44,9 ± 0,9
130	C [*218*]	42,6 ± 0,7	240	C [*231, 4*]	48,5 ± 3,3
133	C [*223, 4*]	45,6 ± 2,4	240	C [*223, 4*]	43,9 ± 2,3
135	C [*212, 4*]	51 ± 6	241,5	C [*224*]	42,7 ± 0,9
135	C [*211*]	56,8 ± 3,2	244,8	C [*224*]	43,1 ± 0,9
140	C [*220, 4*]	42,6 ± 2,7	248,1	C [*224*]	41,0 ± 0,9
144	C [*215, 4*]	49,5 ± 3,6	251,4	C [*224*]	39,3 ± 0,9
150	C [*221*]	55,3 ± 1,6	254,7	C [*224*]	39,8 ± 0,8
152	C [*223, 4*]	59,6 ± 3,0	256	C [*220, 4*]	38,5 ± 1,9
152	C [*219*]	59,7 ± 1,0	258	C [*223, 4*]	38,7 ± 3,4
157	C [*223, 4*]	61,9 ± 2,4	258	C [*224*]	38,8 ± 0,8
158,2	C [*224*]	56,4 + 2,0	261,4	C [*224*]	36,8 ± 0,8
165	C [*225, 4*]	67,5 ± 1,4	265	C [*235*]	43,5 ± 6,0
169	C [*226, 4*]	61,9 ± 3,3	266,5	C [*224*]	35,6 ± 0,8
170	C [*221, 4*]	62,4 ± 1,4	270	C [*231*]	36,5 ± 2,4
171,7	C [*224*]	67,2 ± 1,1	271,6	C [*224*]	33,4 ± 0,8
176	C [*212, 4*]	64 ± 6	276,7	C [*224*]	31,1 ± 0,8
178,4	C [*224*]	67,2 ± 1,1	281,8	C [*224*]	32,4 ± 0,8
179	C [*223, 4*]	65,5 ± 2,5	286,9	C [*224*]	31,6 ± 0,8
184	C [*220, 4*]	65,6 ± 2,4	290	N [*433*]	33 ± 2
185,2	C [*224*]	67,7 ± 1,0	290	C [*220, 4*]	34,8 ± 1,2
187	C [*227*]	63,7 ± 1,3	292	C [*224*]	30,5 ± 0,8
189,9	C [*224*]	67,8 ± 0,8	297,2	C [*224*]	29,3 ± 0,8
194	C [*226, 4*]	69,5 ± 3,8	302,5	C [*224*]	28,9 ± 0,8
194	C [*223, 4*]	64,5 ± 2,5	307	C [*239*]	30,7 ± 1,8
195	C [*223, 4*]	61,8 ± 2,5	307,7	C [*224*]	28,1 ± 0,8
196,2	C [*224*]	64,0 ± 1,1	313	C [*224*]	28,7 ± 0,7
197	C [*220, 4*]	71,5 ± 2,5	318,2	C [*224*]	27,0 ± 0,6
201	C [*224*]	63,8 ± 1,0	323,5	C [*224*]	26,2 ± 0,6
205,8	C [*224*]	59,3 ± 1,0	328,2	C [*224*]	26,4 ± 0,6
209	C [*228*]	57,2 ± 2,9	330	H-DC [*241*]	24 ± 5
210	C [*226, 4*]	61,6 ± 3,8	333	C [*242*]	28,8 ± 1,8
210,6	C [*224*]	58,7 ± 1,1	334,2	C [*224*]	26,0 ± 0,6
215	C [*223, 4*]	55,7 ± 2,2	335	C [*220, 4*]	26,6 ± 1,0

---

*) Calculated by the experimental values of the scattering lengths (see 3.1).

Table IX. (continued)

T	method	σ_t [mb]	T	method	σ_t [mb]
340	C [*235*]	23 ± 11	770	P-BC [*247*]	40 ± 5
345	C [*224*]	24,0 ± 1,0	780	C [*196*]	36 ± 1,1
361	C [*224*]	25,2 ± 1,0	790	C [*246*]	46,1 ± 3,4
363	C [*220, 4*]	26,7 ± 1,0	797	C [*195*]	40,2 ± 1,22
370	N [*433*]	27 ± 2	800	C [*245*]	42 ± 3
373	C [*195*]	28,8 ± 1,4	800	C [*244*]	42,2 ± 1,3
393	C [*220, 4*]	26,2 ± 2,7	800	H-BC [*253*]	53,3 ± 2,4
426	C [*195*]	29,4 ± 1,4	816	C [*195*]	46,37 ± 1,5
427	N [*433*]	27 ± 2	819	C [*195*]	48,2 ± 1,9
450	C [*234*]	25 ± 3	836	C [*195*]	48,13 ± 1,5
450	C [*244*]	30 ± 1,2	840	C [*195*]	55,13 ± 2,1
450	C [*245*]	25,8 ± 3,0	856	C [*195*]	53,32 ± 1,72
450	C [*246*]	28,8 ± 2,7	860	C [*246*]	47,7 ± 2,7
460 ± 20	N [*433*]	28 ± 2	860	C [*244*]	50 ± 1,1
460	P-BC [*247*]	29,9 ± 3,0	860	C [*196*]	40 ± 1,3
468	C [*195*]	29,9 ± 1,2	866	C [*195*]	54,2 ± 1,79
470	C [*248*]	27 ± 5	868	C [*195*]	59,22 ± 2,4
470	C [*196*]	30,0 ± 1,1	880	C [*244*]	53,1 ± 1,6
500	C [*245*]	28,8 ± 4,0	886	C [*195*]	56,76 ± 1,84
500	C [*246*]	31,3 ± 4,8	890	C [*195*]	58,46 ± 2,2
500	C [*244*]	32,8 ± 0,9	890	C [*244*]	55,4 ± 1,25
510	C [*235*]	20 ± 7	900	C [*246*]	44,4 ± 2,3
518	C [*195*]	35,0 ± 1,3	900	C [*196*]	48,5 ± 1,3
540	C [*196*]	31,9 ± 1,1	915	C [*195*]	55,17 ± 1,79
550	C [*244*]	39,1 ± 1,9	918	C [*195*]	55,02 ± 2,4
550	C [*245*]	35,8 ± 3,0	920	C [*244*]	54,5 ± 1,1
550	C [*246*]	37,4 ± 3,0	940	C [*196*]	51 ± 0,9
567	C [*195*]	44,8 ± 1,9	943	C [*195*]	50,67 ± 2,6
580	C [*196*]	36 ± 1,1	945	C [*195*]	48,82 ± 1,63
591	C [*195*]	45,1 ± 1,7	950	C [*244*]	48,9 ± 0,9
600	C [*244*]	43,4 ± 0,9	960	N [*273*]	46,9 ± 4,5
600	P-BC [*247*]	38,7 ± 4,7	960	H-BC [*257*]	48,2 ± 2,5
600	C [*235*]	23 ± 11	965	C [*195*]	45,70 ± 1,62
604	C [*195*]	45,7 ± 1,8	970	C [*196*]	49,5 ± 0,9
610	C [*246*]	37,0 ± 2,1	970	C [*246*]	45,0 ± 2,7
616	C [*195*]	45,3 ± 1,7	972	C [*195*]	44,84 ± 2,2
625	C [*196*]	41,1 ± 1,1	985	C [*195*]	41,52 ± 1,53
643	C [*195*]	44,5 ± 2,2	990	C [*244*]	45 ± 0,8
650	C [*244*]	39,4 ± 1,9	1,0 Bev	C [*246*]	46 ± 3
665	C [*195*]	39,2 ± 1,4	1,0	C [*245*]	48 ± 4
670	C [*246*]	39,5 ± 3,0	1,01	H-BC [*258, 259*]	48,2 ± 3,7
675	C [*245*]	36 ± 3	1,014	C [*195*]	39,54 ± 2,0
680	C [*196*]	42,2 ± 1,1	1,03	C [*244*]	39,8 ± 1,1
700	C [*244*]	35,6 ± 1,2	1,03	C [*196*]	40,5 ± 0,9
700	C [*235*]	42 ± 10	1,064	C [*195*]	36,66 ± 1,3
719	C [*195*]	34,9 ± 1,5	1,076	C [*195*]	35,77 ± 2,0
725	C [*244*]	38,4 ± 0,9	1,08	C [*246*]	36,3 ± 2,6
730	C [*196*]	40,0 ± 1,1	1,08	C [*196*]	37,5 ± 0,9
749	C [*195*]	37,4 ± 1,6	1,096	C [*244*]	36,3 ± 0,9
750	C [*244*]	40 ± 1,9	1,12	C [*196*]	35 ± 0,9
769	C [*195*]	37,4 ± 2,0	1,15	C [*195*]	35,52 ± 2,0

Table IX. (continued)

T	method	σ_t [mb]
1,15	C [*244*]	35,5 ± 0,8
1,164	C [*195*]	34,45 ± 1,32
1,19	C [*244*]	35,1 ± 1,1
1,24	C [*244*]	34,4 ± 0,8
1,25	C [*246*]	29,2 ± 3,7
1,263	C [*195*]	35,72 ± 1,35
1,3	C [*244*]	34,3 ± 1,1
1,33	C [*244*]	34,6 ± 1,0
1,35	C [*246*]	30,1 ± 2,8
1,363	C [*195*]	33,48 ± 1,41
1,37	H-DC [*261*]	34,6 ± 2,7
1,38	C [*246*]	30,8 ± 2,8
1,4	C [*244*]	33,4 ± 0,9
1,46	C [*244*]	33,2 ± 0,8
1,462	C [*195*]	31,81 ± 1,5
1,47	C [*246*]	31,4 ± 1,8
1,50	C [*246*]	30,0 ± 2,0
1,5	C [*245*]	34 ± 3
1,52	C [*244*]	32,5 ± 1,3
1,57	C [*244*]	31,9 ± 0,6
1,65	C [*244*]	26,2 ± 2,5
1,67	C [*246*]	31,4 ± 3,9
1,71	H-DC [*263*]	31,4 ± 3,9
1,9	C [*246*]	31,3 ± 1,6
4,16	C [*264*]	28,7 ± 2,6
4,4	C [*265*]	30 ± 5
4,5	N [*266*]	20,4 ± 3,5
4,6	C [*89*]	32
4,7	N [*267*]	28
4,7	H-DC [*268*]	24,5 ± 2,4
4,85	C [*89*]	32,2
5,03	H-BC [*269*]	29,1 ± 2,9
5,1	C [*89*]	30,9
5,1	N [*270*]	29 ± 3
5,2	N [*270*]	29,1 ± 2,9
5,35	N [*89*]	29,7
5,6	C [*89*]	30,2
5,85	C [*89*]	30,7
6,1	C [*89*]	29,5
6,6	C [*89*]	30,9
6,65	P-BC [*272*]	28,2 ± 2,3
6,85	C [*324*]	27,8 ± 0,8
6,85	C [*89*]	29,7
7,35	C [*89*]	29,3
8,35	C [*89*]	29,3
8,85	C [*324*]	25 ± 4
9,0	C [*89*]	29
9,85	C [*89*]	29
14,0	C [*312*]	33 ± 4
16,0	C [*323*]	26,5 ± 1,7
16,0	H-BC [*275*]	26,5 ± 1,7

interactions with the production of neutral particles only. At high energies it is not essential, as far as $\sigma_{ex} \ll \sigma_{in}$.

The values of $\sigma_t(\pi^- N)$ in Table XIV are calculated according to the optical theory from the experimental values of the mean free path of π^--mesons in emulsions. The errors indicated in these cases in $\delta\sigma_t$ correspond to the experimental errors in the values of the range δL. As we see, the values of σ_t thus obtained are in good agreement with the values of σ_t from Tables IX and XII. The agreement here is much better than in the case of pN interaction we have considered above The main experimental data are summarized in Figs. 5 and 6.

The equalities [*5*] for the cross sections σ_t, σ_{el}, σ_{in}

$$\sigma(\pi^+ p) = \sigma(\pi^- n) = \sigma(\pi^- \overline{p}) = \sigma(\pi^+ \overline{n})$$

$$\sigma(\pi^- p) = \sigma(\pi^+ n) = \sigma(\pi^+ \overline{p}) = \sigma(\pi^- \overline{n})$$

$$\sigma(\pi^0 p) = \sigma(\pi^0 n) = \sigma(\pi^0 \overline{p}) = \sigma(\pi^0 \overline{n})$$

follow from the considerations of the charge symmetry and invariance with respect to the charge conjugation

Besides,

$$\sigma_{ex}(\pi^0 p) = \sigma_{ex}(\pi^- p) = \sigma_{ex}(\pi^0 n) = \sigma_{ex}(\pi^0 \overline{p}) =$$

$$= \sigma_{ex}(\pi^+ n) = \sigma_{ex}(\pi^+ \overline{p}) = \sigma_{ex}(\pi^- \overline{n}).$$

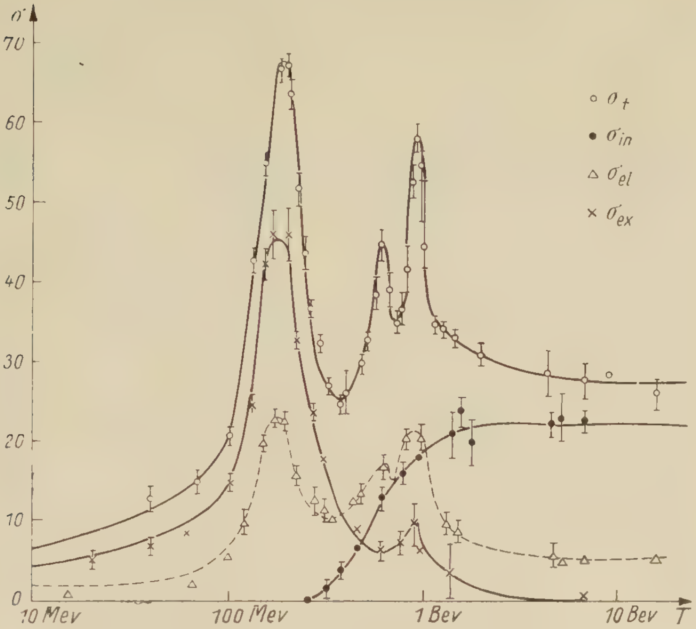

Fig. 5. Cross sections for π^--meson interactions with protons. The values of σ are given in the units of 10^{-27} cm².

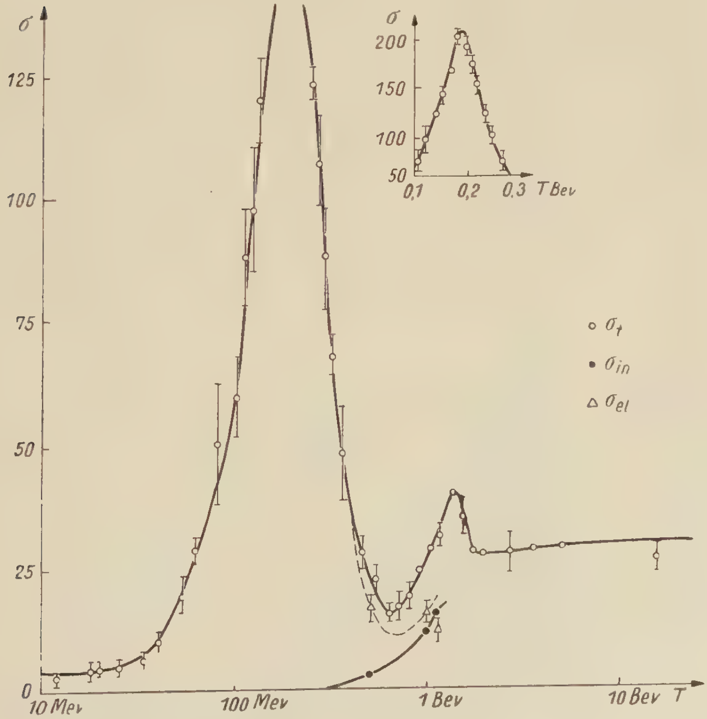

Fig. 6. Cross sections for π^+-meson interactions with protons. The values of σ are given in the units of 10^{-27} cm².

Table X. π^-p interaction

T	method	σ_{el} [mb]	σ_{ex} [mb]
0 Mev	*)	2,0 ± 0,1	3,8 ± 0,2
15	H-DC [*197*]	1,77 ± 0,66	—
18,5	H-BC [*198*]	1,32 ± 0,20	—
20	C [*199*]	—	5,0 ± 0,8
30	C [*199*)	—	5,7 ± 0,9
34	C [*201*]	—	5,0 ± 1,5
40	C [*203*]	—	7,9 ± 1,8
42	C [*199*]	—	6,9 ± 1,2
61	C [*207*]	—	7,7 ± 0,6
65	C [*206*]	2,5 ± 0,5	12,4 ± 1,5
75	Em [*209*]	∼ 3	—
95	C [*207*]	—	13,2 ± 0,8
98	C [*213*]	6,15 ± 0,22	15,0 ± 0,8
118	C [*214*]	9,6 ± 2,0	—
120	C [*215*]	10,1 ± 1,6	21,5 ± 2,7
128	H-DC [*216*]	12,8 ± 1,0	—
128	C [*217*]	—	25,1 ± 1,3
130	C [*218*]	∼12	—
135	C [*211*]	16,2 ± 2,3	40,6 ± 2,4
144	C [*215*]	15,9 ± 2,4	30,5 ± 3,8
150	C [*221*]	20 ± 1	34,6 ± 1,2
150	C [*222*]	—	42,6 ± 1,9
152	C [*219*]	18,8	—
162	H-DC [*216*]	21,4 ± 1,2	—
165	C [*225*]	21,2 ± 1,5	46,5 ± 3,5
169	C [*226*]	20,1 ± 2,0	40,9 ± 2,9
170	C [*221*]	23,3 ± 1,0	39,1 ± 2,0
187	C [*227*]	22,9 ± 1,3	42,2 ± 1,5
194	C [*226*]	25,7 ± 2,7	46,3 ± 3,6
210	C [*226*]	28,4 ± 3,1	33,6 ± 3,6
217	C [*228*]	19,7 ± 2,3	36,6 ± 2,4
220	C [*229*]	20,1 ± 0,6	33,3 ± 0,7
224	H-BC [*230*]	16,0 ± 0,8	34,4 ± 1,9
230	C [*250, 447*]	20,8 ± 0,4	30,4 ± 1,3
240	C [*232*]	—	30,0 ± 1,4
240	C [*233*]	15,1 ± 0,8	—
260	C [*447*]	—	25,4 ± 1,0
270	C [*232*]	—	23,9 ± 1,1
290	C [*250, 447*]	13,8 ± 0,3	18,2 ± 0,8
300	C [*236*]	11,7 ± 1,5	—
300	Em [*237*]	13 ± 2	—
307	C [*232*]	—	17,8 ± 1,0
307	C [*233*]	11,4 ± 0,8	—
317	C [*447*]	—	17,6 ± 0,8
330	H-DC [*241*]	11 ± 4	13 ± 4
333	C [*232*]	—	18,0 ± 1,1
333	C [*233*]	10,3 ± 0,6	—
370	C [*243*]	10,8 ± 0,2	—
370	C [*250, 447*]	10,9 ± 0,2	13,6 ± 0,6

---

*) Calculated by the experimental values of the scattering lengths (see 3.1).

Table X. (continued)

T	method	σ_{el} [ml]	σ_{ex} [mb]
427	C [*234, 433*]	$13{,}0 \pm 0{,}34$	$10{,}3 \pm 2{,}3$
460	P-BC [*247*]	$13{,}8 \pm 1{,}0$	$9{,}1 \pm 1{,}2$
600	P-BC [*247*]	$23{,}3 \pm 2{,}5$**)	$8 \pm 1{,}5$**)
610	P-BC [*249*]	$16{,}6 \pm 2{,}2$	—
655	P-BC [*249*]	$16{,}1 \pm 1{,}6$	—
750	P-BC [*249*]	$14{,}4 \pm 1{,}3$	—
770 ± 75	P-BC [*247*]	$16{,}7 \pm 2{,}0$	$7{,}35 \pm 1{,}2$
800	C [*195, 196, 246*]	$\sim 16{,}4$	$\sim 7{,}3$
800	H-BC [*253*]	21 ± 1	~ 10
810	N [*321*]	$21{,}0 \pm 1{,}2$	—
900	Em [*254*]	$23 \pm 3{,}7$**)	$\leq 12{,}5 \pm 3{,}7$**)
915	P-BC [*255*]	19,8	—
950	H-BC [*256*]	$20{,}8 \pm 1{,}7$**)	< 9**)
960	N [*273*]	19 ± 2	$< 7{,}6 \pm 0{,}8$
960	H-DC [*254*]	20 ± 3	—
960	H-BC [*257*]	$20{,}8 \pm 1{,}5$	$< 3{,}1 \pm 0{,}4$
1,01 Bev	H-BC [*258, 259*]	$22 \pm 3{,}1$	—
1,3	P-BC [*260*]	$10 \pm 0{,}8$	—
1,37	H-DC [*261*]	$10{,}0 \pm 0{,}8$	$< 3{,}7 \pm 3{,}7$
1,4	Em [*445*]	9 ± 1	—
1,4	N [*262*]	10 ± 2	—
1,5	Em [*322*]	$9{,}0 \pm 1{,}5$	—
1,72	H-DC [*106*]	$11{,}1 \pm 2{,}3$	—
2,66	P-BC [*274*]	—	$< 0{,}2 \pm 0{,}25$
4,5	Em [*263*]	$4{,}5 \pm 1$	—
4,7	N [*267*]	$6{,}0 \pm 1{,}5$	
4,7	H-DC [*268*]	$4{,}7 \pm 1{,}0$	
5,03	H-BC [*269*]	$5{,}6 \pm 0{,}5$	—
6,65	P-BC [*271*]	$6 \pm 0{,}5$	—
6,65	P-BC [*238*]	—	$< 1{,}0 \pm 0{,}3$
16	H-BC [*275*]	6	—

**) Renormalized to a more accurate value of σ_t.

In table XV are given the values of the energy T_{max}, spin J and the isotopic spin t, for which the resonance πN interaction is observed. The values of T_{max} for the three last resonances are indicated by the data of paper [*195*]. These values are somewhat different from those in [*146*]. The reason for such a difference is not at present clear. It is very likely to be due to the difference in scaling. It should be emphasized that the values of J given in the Table for the maxima at $T = 605$ Mev and $T = 890$ Mev are not yet quite reliable [*4*].

As is seen from Figs. 5 and 6, the values of the cross sections for π^+p and π^-p interactions are compared. They become independent of energy practicalli already at $T = 4$ Bev. The limiting value of $\sigma_t \simeq 29$ mb; $\sigma_{el} \simeq 6$ mb; $\sigma_{in} \sim 23$ mb; $\sigma_{ex} \simeq 0$.

At the present time there is still an insufficient data on the π^0-meson interaction with nucleons, especially at high energies. However, the magnitude of the total cross section for $\pi^0 p$ interaction may be determined from the charge symmetry considerations:

$$\sigma_t(\pi^0 p) = \tfrac{1}{2}\,[\sigma_t(\pi^- p) + \sigma_t(\pi^+ p)].$$

At high energies this cross section is close to the cross sections for charged π-meson interaction with nucleons.

Table XI. $\pi^- p$ interaction

T	method	σ_{in} [mb]
Below the threshold for π^0-meson production $T = 175$ Mev $\sigma_{in} = 0$.		
224 Mev	H-BC [*230*]	0,09 ± 0,04
230	C [*250, 433*]	>0,3 ± 0,3
245	Em [*251*]	0,2 ± 0,1
260	C [*234*]	0,3 ± 0,2
290	Em [*252*]	1,3 ± 0,3
290	C [*433, 447*]	>2,4 ± 0,8
307	C [*240*]	1,47 ± 0,10
317	C [*234*]	1,5 ± 0,4
333	C [*240*]	2,5 ± 0,1
370	C [*433, 447*]	>3,1 ± 0,8
370	C [*240*]	4,3 ± 0,1
371	C [*234*]	4,1 ± 0,8
427	C [*234*]	7,2 ± 0,2
460	P-BC [*247*]	7,0 ± 1,0
600	P-BC [*247*]	16,2 ± 1,7*)
770 ± 75	P-BC [*247*]	16,0 ± 1,4
800	C [*195, 196, 246*]	17,3
800	H-BC [*253*]	22,3 ± 1,5
900	Em [*254*]	21,7 ± 3,7*)
950	H-BC [*256*]	> 20 ± 1,6*)
960	N [*273*]	20 ± 3,2
960	H-DC [*254*]	18,3 ± 2
960	H-BC [*257*]	24,3 ± 1,3
1,01 Bev	H-BC [*258, 259*]	25,2 ± 2,5
1,2	P-BC [*434*]	12 ± 0,8
1,3	P-BC [*260*]	20
1,37	H-DC [*261*]	20,9 ± 3,5
1,4	N [*262*]	24
1,5	Em [*232*]	24 ± 2,5
1,71	H-DC [*263*]	≥20,3 ± 3
4,5	Em [*263*]	24,5 ± 1,7
4,7	N [*267*]	22
4,7	H-DC [*268*]	17,7 ± 2
5	H-BC [*269*]	23,5 ± 3,4
6,65	P-BC [*272*]	$22{,}7^{+1,8}_{-2,8}$

*) Renormalized to a more exact value of σ_t.

From the theoretical considerations on the weak dependence of interactions on isotopic spins at high energies (see further), one should expect that the cross sections:

$$\sigma_{el}(\pi^0 p) = \tfrac{1}{2}\,[\sigma_{el}(\pi^- p) + \sigma_{el}(\pi^+ p) - \sigma_{ex}(\pi^0 p)]$$

and

$$\sigma_{in}(\pi^0 p) = \tfrac{1}{2}\,[\sigma_{in}(\pi^- p) + \sigma_{in}(\pi^+ p) + \sigma_{ex}(\pi^0 p)]$$

will be also close to the corresponding cross sections for charged π-mesons8).

2.4. Interaction of Pions with Hyperons

Such a kind of interaction was considered long ago in theoretical papers in the calculations of hyperon interactions with nucleons (see e. g., [*405*] and review [*406*], where a detailed bibriography is given). One can expect that at high energies the cross sections $\sigma(\pi\Lambda)$, $\sigma(\pi\Sigma)$, $\sigma(\pi N)$ will be close by their magnitude. However, until very recently whatever experimental data have been completely absent.

---

8) The charge exchange cross section σ_{ex} is included into each of the cross sections σ_{in} (cf. page 17).

Table XII. π^-p interaction

T	method	σ_t [mb]	T	method	σ_t [mb]
0 Mev	*)	1,9 ± 0,2	136	C [*286*]	152 ± 14
6	H-BC [*276*]	1,6 ± 0,8	136	D-BC [*313*]	120 ± 10
8	H-BC [*276*]	2,6 ± 0,8	140	C [*292, 4*]	135 ± 8
12	H-BC [*276*]	3,2 ± 0,8	142	C [*223*]	150 ± 8
18	H-BC [*276*]	4,7 ± 0,3	143	C [*294, 4*]	140,5 ± 7,4
20	N [*277*]	4,5 ± 0,9	144	C [*292, 4*]	153 ± 4,3
21,5	C [*279*]	3,3 ± 0,3	145	Em [*293*]	169 ± 23
23	H-BC [*276*]	4,8 ± 0,5	146	C [*235, 4*]	150 ± 9,1
23	Em [*278*]	~ 5,5	150	C [*295*]	129 ± 19
24,8	C [*280*]	4,4 ± 1,3	150	C [*221, 4*]	166,0 ± 4,3
31,5	C [*281*]	4,7 ± 0,4	151	Em [*296,4*]	161 ± 20
33	C [*282*]	6,4 ± 2,1	151	Em [*297*]	152 ± 31
37	C [*307*]	6,5 ± 0,5	152	C [*223, 4*]	174 ± 6
37	C [*202, 4*]	12,6 ± 1,2	156	C [*223, 4*]	168 ± 5
38	C [*308, 4*]	7,9 ± 1,4	157	C [*235, 4*]	162 ± 8,6
40	C [*283, 4*]	13,3 ± 2,3	162	C [*294, 4*]	170,5 ± 3,8
41,5	C [*284*]	10,0 ± 1,0	164	C [*292, 4*]	170 ± 5,1
44	C [*282, 4*]	12,4 ± 2,7	165	C [*225, 4*]	189,6 ± 4,9
45	Em [*285, 4*]	10 ± 2,2	166	C [*235, 4*]	179,4 ± 4,8
53	H-DC [*309, 4*]	19,2 ± 3,6	166	C [*223, 4*]	187,6 ± 5,3
56	C [*282, 4*]	19,2 ± 3,6	170	C [*294, 4*]	198 ± 3,7
56	C [*286*]	20 ± 10	170	C [*221, 4*]	194,9 ± 4,3
58	C [*206, 4*]	15,5 ± 2,0	171	C [*223, 4*]	202 ± 4
58	C [*205, 4*]	28,8 ± 2,5	171	C [*235, 4*]	204 ± 6,4
65	C [*206*]	20,4 ± 2,0	173	C [*235, 4*]	205 ± 6,1
70	C [*282, 4*]	21,4 ± 5,5	173,5	C [*294*]	193,5 ± 3,5
75	Em [*209, 4*]	45 ± 15	174	C [*292, 4*]	193,3 ± 6
78	C [*215*]	32,2 ± 3,8	176	C [*298, 4*]	197,7 ± 7,3
78	P-BC [*446*]	39 ± 6	177	C [*294*]	198 ± 5
79	C [*208, 4*]	48,3 ± 10	180	C [*295*]	146 ± 18
82	C [*286*]	50 ± 13	181	C [*235*]	187 ± 7
83	Em [*287, 4*]	34,5 ± 6,9	182	C [*223, 4*]	174 ± 20
100	Em [*289, 4*]	59,0 ± 8,0	183,5	C [*294*]	192 ± 3,5
109	C [*208, 4*]	88,0 ± 11,4	184	C [*292, 4*]	195,7 ± 6
110	C [*215*]	79,5 ± 4,2	185	C [*223, 4*]	187 ± 8,5
110	C [*211, 4*]	76,4 ± 7,7	188	Em [*297, 4*]	158 ± 34
113	Em [*290, 4*]	80 ± 6,5	189	C [*299, 4*]	194,0 ± 4,4
114	Em [*288*]	83	189	C [*235*]	182 ± 7
115	C [*208, 4*]	99 ± 15	194	C [*292, 4*]	196 ± 6
118	C [*286*]	91 ± 6	195	C [*294*]	174 ± 4
119	P-BC [*291*]	93 ± 12	196	C [*223*]	202 ± 14
120	Em [*306, 4*]	97,5 ± 12	200	C [*298, 4*]	183 ± 6
124	Em [*288*]	106	205	C [*294, 4*]	178 ± 4,9
127	C [*208, 4*]	13,8 ± 17,5	209	C [*292, 4*]	177,4 ± 6,2
128	C [*223, 4*]	120,3 ± 9,3	210	C [*235, 4*]	148 ± 22
133	C [*208, 4*]	157 ± 19	214	C [*235, 4*]	141 ± 9,4
135	C [*215*]	141,4 ± 11,5	216,5	Em [*310, 4*]	165 ± 19
135	C [*223, 4*]	125,1 ± 4	219	C [*292, 4*]	154,1 ± 7,2
135	C [*211, 4*]	123 ± 19	220	C [*229, 4*]	140 ± 5,2

---

*) Calculated by the experimental values of the scattering lengths (see 3.1).

Table XII. (continued)

T	method	σ_t [ml]	T	method	σ_t [ml]
222	C [*235, 3*]	148 ± 9,7	965	C [*195*]	23,8 ± 0,78
225	H-DC [*300, 4*]	142 ± 18	990	H-BC [*451*]	27,9 ± 3,6
229	C [*292, 4*]	130 ± 7,2	1 Bev	C [*246*]	23,5 ± 1,5
240	C [*298, 4*]	124,2 ± 2,3	1,0	C [*244*]	27,6 ± 1,2
262	C [*235, 4*]	111 ± 8,7	1,014	C [*195*]	25,85 ± 0,84
263	C [*235, 4*]	107 ± 8,8	1,04	C [*244*]	28,40 ± 1,12
270	C [*298, 4*]	81,3 ± 2,2	1,064	C [*195*]	26,78 ± 0,94
280	C [*235*]	88 ± 11	1,07	C [*246*]	27,3 ± 3,7
295	Em [*237*]	63 ± 10	1,09	C [*196*]	27,4 ± 1,3
298	C [*235, 4*]	75 ± 6,2	1,1	C [*244*]	31,2 ± 0,6
307	C [*298, 4*]	65,5 ± 1,7	1,114	C [*195*]	27,51 ± 1,07
335	C [*235, 4*]	53 ± 5,9	1,14	C [*244*]	35,0 ± 1,2
340	C [*235*]	48 ± 9	1,15	C [*246*]	31,3 ± 1,7
376	C [*195*]	40,39 ± 1,62	1,164	C [*195*]	30,65 ± 1,19
450	C [*235, 4*]	27,5 ± 6,3	1,18	C [*244*]	36,3 ± 0,6
450	C [*245*]	22,5 ± 3	1,213	C [*195*]	35,27 ± 1,37
450	C [*246, 4*]	24,8 ± 3,6	1,24	C [*244*]	38,8 ± 0,8
460	C [*304*]	28,4 ± 2,5	1,25	C [*246*]	38,8 ± 2,5
469	C [*195*]	23,47 ± 1,08	1,263	C [*195*]	36,64 ± 1,56
510	C [*304*]	24,1 ± 0,9	1,288	C [*195*]	37,37 ± 1,45
533	C [*304*]	22,5 ± 2,5	1,3	C [*77*]	39,4 ± 0,6
550	C [*246*]	16,1 ± 2,5	1,313	C [*195*]	38,07 ± 1,47
550	C [*245*]	14,5 ± 3,0	1,33	C [*77*]	39,1 ± 0,8
567	C [*195*]	17,26 ± 0,82	1,338	C [*195*]	37,65 ± 1,54
575	C [*304*]	21,5 ± 1,9	1,34	C [*244*]	40,3 ± 0,9
626	C [*195*]	15,11 ± 0,72	1,363	C [*195*]	36,16 ± 1,56
628	C [*196*]	13,7 ± 1,3	1,38	C [*246*]	41,4 ± 3,0
650	C [*304*]	17,2 ± 1,5	1,412	C [*195*]	36,53 ± 1,60
664	C [*195*]	14,75 ± 0,67	1,44	C [*244*]	38,7 ± 0,8
670	C [*246*]	14,5 ± 2,0	1,462	C [*195*]	34,10 ± 1,59
675	C [*245*]	13,1 ± 3,0	1,47	C [*77*]	35,8 ± 0,9
685	C [*196*]	14,14 ± 1,3	1,50	C [*246*]	35,3 ± 2,5
700	C [*235*]	17 ± 3	1,51	C [*244*]	37,6 ± 1,2
734	C [*196*]	17,1 ± 1,3	1,60	C [*77*]	30,1 ± 0,5
750	C [*304*]	20,9 ± 0,9	1,67	C [*246*]	32,6 ± 1,8
770	C [*195*]	19,44 ± 0,8	1,76	C [*77*]	28,4 ± 0,6
788	C [*196*]	18,3 ± 1,3	1,91	C [*77*]	27,8 ± 0,6
790	C [*246*]	19,5 ± 2,0	2,33	C [*77*]	29,0 ± 0,6
798	C [*196*]	16,5 ± 1,3	2,76	C [*303*]	28 ± 4
810	C [*244*]	23,3 ± 2,0	2,83	C [*77*]	29,2 ± 0,5
816	C [*195*]	21,40 ± 0,81	3,44	C [*77*]	29,2 ± 0,4
838	C [*195*]	22,49 ± 0,83	3,55	C [*311*]	30,0 ± 1,2
860	C [*244*]	25,6 ± 1,2	3,86	C [*77*]	29,3 ± 0,4
863	C [*195*]	21,88 ± 0,86	4,3	C [*311*]	28 ± 4
866	C [*195*]	23,40 ± 0,65	4,6	C [*311*]	31 ± 1,2
890	C [*244*]	24,9	4,66	C [*453*]	29,4 ± 1,4
910	C [*244*]	25,8 ± 1,1	5	C [*89*]	30,3
915	C [*195*]	23,12 ± 0,74	10	C [*89*]	26,5
947	C [*196*]	21,3 ± 1,3	14	C [*312*]	26 ± 4
960	C [*244*]	25,7 ± 0,9			

Table XIII. π^+p interaction

T	method	σ_{el} [mb]	σ_{in} [mb]
Below the threshold for π°-meson production $T = 175$ Mev $\sigma_{el} = \sigma_t$ and $\sigma_{in} = 0$			
500 Mev	H-BC [*305*]	$17{,}2 \pm 3{,}0$	$2{,}9 \pm 0{,}9$
990 Mev	H-BC [*451*]	$15{,}3 \pm 1{,}5$	$12{,}6 \pm 3{,}3$
1,1 Bev	H-BC [*301*]	$12{,}3 \pm 1{,}2$	$15{,}2 \pm 2{,}5$

Table XIV. π^-N interaction

T [Bev]	Range in emulsions L [cm]	σ_t [mb]
1,0 [*254*]	38 ± 3	29 ± 6
1,5 [*302*]	35 ± 1	$35 \pm 2{,}5$
3 [*314*]	$35{,}5 \pm 5$	$34^{+18{,}5}_{-11}$
4,2 [*315*]	$38{,}7 \pm 3{,}5$	27^{+8}_{-5}
4,3 [*316*]	$33{,}7 \pm 4{,}7$	39^{+21}_{-12}
5,7 [*317*]	41 ± 6	24^{+11}_{-6}
6,8 [*318*]	35 ± 3	35^{+10}_{-6}
7,5 [*319*]	38 ± 2	29 ± 4
50 [*320*]	37 ± 6	30^{+20}_{-8}
(The mean value by the interval 1 ÷ 200 Bev)		
230 [*450*]	41 ± 8*)	24^{+16}_{-8}

---

*) Strictly speaking, this value L in paper [*450*] is given as a mean free path for all shower particles produced in the collision of a primary particle. As far as the major part of the shower particles consists of pions, one may think that within the experimental error this value of L is equal to the pion range.

Table XV. Resonance πN interaction

T [Mev]	J	t
180 ± 2	$P_{3/2}$	3/2
605 ± 6	$D_{3/2}$ or $P_{3/2}$	1/2
890 ± 9	$D_{5/2}$ or $F_{3/2}$; or the both together	1/2
1330 ± 30	$D_{3/2} + \cdots$	3/2

In recent papers [*325*, *326*] a conclusion was obtained about the resonance $\pi\Lambda$ interaction at $T \simeq 150 \pm 20$ Mev from the analysis of the correlations between $\pi^{\pm}$-mesons on the one hand, and a Λ-particle, produced in the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$ at $T = 740$ and 410 Mev. The experimental data are in better agreement with the assumption that the resonance takes place in the state with spin $P = \frac{3}{2}$ although the assumption on the spin $P = \frac{1}{2}$ cannot be given up yet.

The isotopic spin $t = 1$.

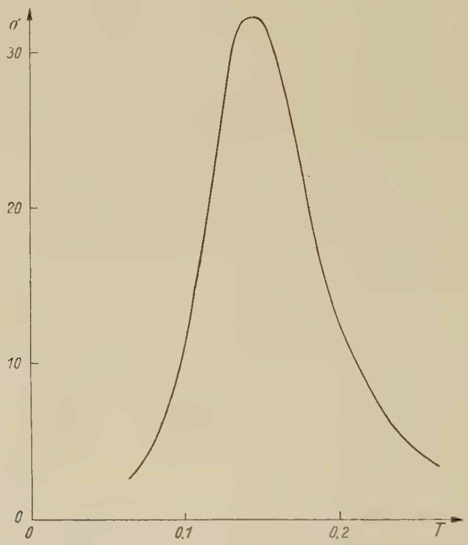

Fig. 7. Cross sections for π-meson interactions with Λ-hyperons. The values of σ are given in arbitrary units.

Fig. 7 shows the energy dependence of the cross section $\sigma(\pi\Lambda)$ in the resonance region. It was calculated in [*325*] by the experimental data on $\pi\Lambda$ resonance. (The values of the cross section $\sigma(\pi\Lambda)$ are indicated in relative units).

From the symmetry considerations one can also expect a resonance in $\pi\Sigma$ interaction. The experimental data point to the existence of such a resonance at $T \simeq 125$ Mev [*327*].

As is seen, the resonance energies in pion interaction with Λ- and Σ-hyperons are close to each other and are not very different from the resonance energy for πN interaction.

2.5 $\pi\pi$-Interaction

At present it becomes more and more evident that a further progress in the physics of elementary particles depends to a great extent on the investigation of the properties $\pi\pi$ interaction. However, all the available information on these interactions is still very poor, and has a tentative and qualitative character. The main difficulty here is that the evidence of $\pi\pi$ interaction can be obtained now only from the analysis fo indirect experimental data.

Not long ago MANDELSTAM, CHEW and other suceeded in formulating a system of equations determining the amplitude of elastic $\pi\pi$ scattering up to the energies of some hundred Mev [*398*]. However, the solution of this system of equations have not yet been obtained.

In paper [*328*], from the analysis of the reaction $\pi + p \rightarrow n + \pi^- + \pi^+$ at $T = 290$ Mev, $\pi\pi$ charge exchange cross section has been estimated to be

$$\sigma_{\mathrm{ex}}(\pi\pi) = 4^{+6}_{-4}\ \mathrm{mb}.$$

at zero pion energy. The phase shift analysis of πN and NN interactions at high energies $T \gg 1$ Bev yields the magnitude of $\pi\pi$ interaction cross section close to the cross sections for πN and NN interactions. Just the same conclusion is obtained from the analysis of the angular asymmetry of particles produced in the collisions of high energy pions with nucleons [*399*], as well as from the study of the multiple production of particles in the cosmic rays at very high energies [*400*].

These results may be illustrated by the following rough qualitative considerations. Let us represent the cross sections for inelastic NN and πN interactions as

$$\sigma(\mathrm{NN}) = 4\pi r_{\mathrm{N}}^2$$

$$\sigma(\pi\mathrm{N}) = \pi(r_{\mathrm{N}} + r_\pi)^2.$$

Hence,

$$r_\pi = r_{\mathrm{N}}\left(2\sqrt{\frac{\sigma(\pi\mathrm{N})}{\sigma(\mathrm{NN})}} - 1\right).$$

At high energies, when the wave length of the interacting particles is very small $\lambda \ll r_{\mathrm{N}}, r_\pi$, the quantities r_{N} and r_π may be treated as effective dimensions of a nucleon and meson. Since, at $T \gtrsim 1$ Bev $\sigma(\pi\mathrm{N})/\sigma(\mathrm{NN}) \simeq \frac{2}{3}$, then $r_\pi \simeq 0{,}7\, r_{\mathrm{N}}$ and the cross sections for inelastic $\pi\pi$ interactions

$$\sigma(\pi\pi) \simeq 4\pi r_\pi^2 \simeq 0{,}5 \cdot \sigma(\mathrm{NN}).$$

Of course, the coefficient 0,5 cannot be taken seriously: one can only say that $\sigma(\pi\pi) \sim \sigma(\mathrm{NN})$.

Close are also the cross sections for elastic scattering $\sigma_{\mathrm{el}} \simeq \sigma_{\mathrm{d}}$ (Let us remind, that the differential scattering is fully determined by inelastic processes).

As has been emphasized in paper [*401*], the lower limit of the cross section for $\pi\pi$ interaction $\sigma_{\mathrm{in}}(\pi\pi) > \delta_{\mathrm{mb}}$. may be obtained if pions are considered as consisting of point ("bare") nucleon and antinucleon. The account of the effective dimensions of these virtual particles increases some times the magnitude of the cross section (cf. [*402*]).

Recently the problem about the existence of the resonance $\pi\pi$ interactions has begun widely discussed in literature. Such an interaction at $T = 400$ Mev in the P-state with the isotopic spin $t = 1$ was suggested by TAKEDA long ago to account for the experiments on inelastic πN interactions [*329*]. Having the same aim in view, DYSON proposed the resonance interaction in the S-state with the isotopic $t = 0$ [*329*]. (See also [*330*].) In papers [*331*], the hypothesis of the resonant $\pi\pi$ interaction was applied to explain the experiments on slow antinucleon annihilation, the agreement of the theory with the experiment being considerably improved.

The study of the electromagnetic nucleon structure with the help of dispersion relations leads also one to the conclusion about the existence of the resonant $\pi\pi$ interaction. In this case the agreement with the experimental data is improved to a great extent, if $\pi\pi$ interaction at the energies $T = (400 \div 900)$ Mev has a resonance in the P-state with the isotopic spin $t = 1$. (This corresponds to the mass of the "pion isobar" $n_\pi \simeq 3\mu - 4\mu$, where μ is the pion mass) [*332*].

It has been emphasized in papers [*397*], that a direct experimental check of the resonance existence in pion interaction can be performed from the analysis of inelastic interactions of electrons with positrons. A theoretical interpretation of the experiments in this case is quite unambiguous. However, at present the arrangement of these experiments is impeded, by the absense of the counter beams of fast electrons and positrons.

Not long ago Ho Tzo-hsiu and Chou Kuang-chao noticed [*333*], that a convenient method for checking the assumption about $\pi\pi$-resonance is the study of the energy spectra of the reactions

$$\pi^\pm + He^4 \to He^4 + \pi^\pm + \pi^0$$

$$\pi^\pm + d \to d + \pi^\pm + \pi^0$$

$$p + p \to d + \pi^+ + \pi^0.$$

In the initial state of all these reactions the isotopic spin is $t = 1$. Therefore, in the final state a pair of pions also has $t = 1$ and is in the state whith an odd orbital momentum. In the low energy region these pions are mainly in the P-state. The presence of $\pi\pi$ resonance in the P-state will lead to a sharp maximum in the energy spectra of He^4 and D-nuclei. If such a resonance does not exist, then the spectra of He^4 and D are changing smoothly, and determined mainly by the statistical phase factors.

In [*334*] are presented the experimental results on an analogous investication of the reactions

$$p + d \to He^3 + \pi^+$$

$$p + d \to He^3 + \pi^+ + \pi^0.$$

It has been found out that in the spectrum of He^3 nuclei there is. indeed, a maximum. However, its position does not agree with the theoretical predictions. It is very likely to be not due to $\pi\pi$ interaction. As far as in [*334*] only the preliminary results have been obtained, any conclusions seem to be so far premature.

By analysing the experimental data on τ-decays with the aid of dispersion relations Wolf and Zöllner arrived very recently to a conclusion that the resonance $\pi\pi$ interaction is possible in the S-state at $t = 2$. At the same time it is not excluded that there exists a resonance in the P-state as well [*449*].

2.6 K-meson Interaction with Nucleons

Tables XVI—XXII and Figs. 8 and 9 show the experimental values of the cross sections for the interaction of charged K-mesons with nucleons.

In most of the cases these cross sections are averaged over large energy intervals. These intervals (if they are indicated in original papers) and the corresponding mean energies are given in the Tables.

In the low energy region a part of the cross sections has been obtained from the analysis of the data on the K-meson interaction with the emulsion nuclei. The details concerning the method of such an analysis can be found, for instance, in paper [*389*].

Some of the cross sections for K±-meson interaction with neutrons have been obtained by the difference method from the experiments with hydrogen and deuterium:

$$\sigma_t(K^{\pm}n) = \sigma_t(K^{\pm}d) - \sigma_t(K^{\pm}p) + I(K^{\pm}d).$$

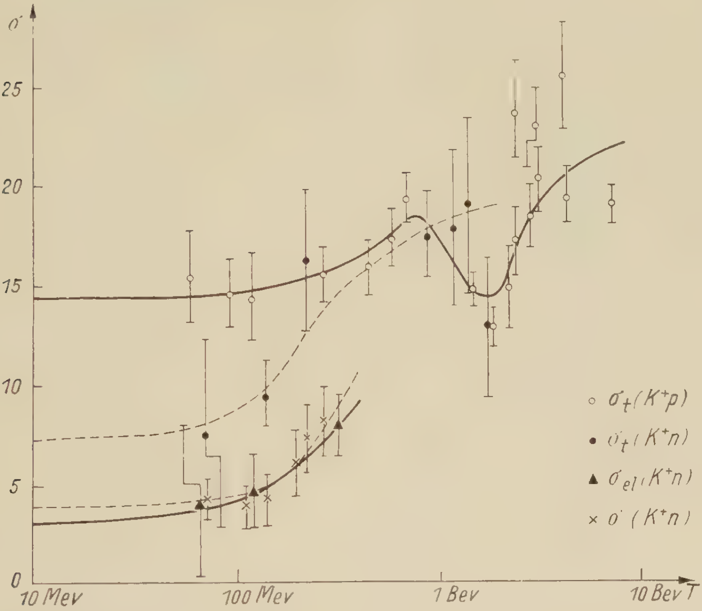

Fig. 8. Cross sections for K+-meson interactions with proton and neutrons.
The dashed lines indicate the cross sections $\sigma_t(K^+n)$ and $\sigma_{ex}(K^+n)$. The values of σ are given in the units of 10^{-27} cm².

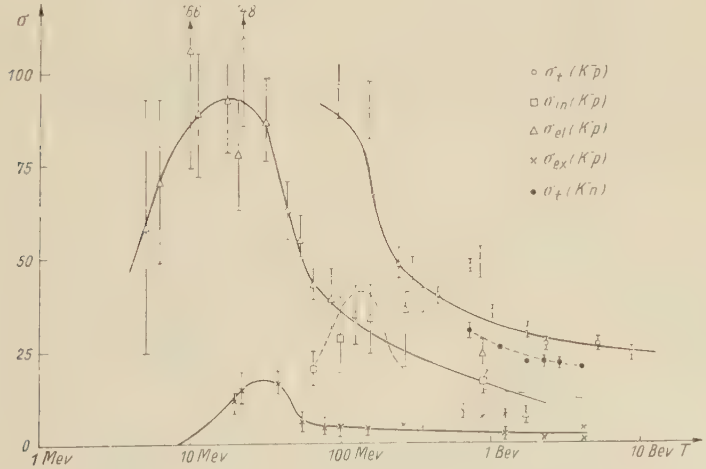

Fig. 9. Cross sections for K−-meson interactions with protons and neutrons. The dashed line is referred to the cross section $\sigma_{in}(K^-p)$.
The values of σ are given in the units of 10^{-27} cm².

Table XVI. K^+p interaction

T	method	σ_t [mb]
Below the threshold for pion production π°-meson $T = 225$ Mev cross sections $\sigma_t = \sigma_{el}$ and $\sigma_{in} = 0$		
0 Mev	*)	$14{,}3 \pm 2{,}4$
10 (0 ÷ 20)	P-BC [*363*]	$4{,}6 \pm 4{,}0$
30 (20 ÷ 40)	P-BC [*363*]	$5{,}8 \pm 3{,}3$
50 (20 ÷ 40)	P-BC [*363*]	$10{,}4 \pm 3{,}3$
50 (30 ÷ 65)	Em [*364*]	~ 15
55 (20 ÷ 90)	P-BC [*363*]	$9{,}4 \pm 1{,}7$
55 (0 ÷ 110)	Em [*376*]	23 ± 7
60 (20 ÷ 100)	Em [*367*]	$13{,}5 \pm 2{,}8$
60 (20 ÷ 100)	Em [*365*]	$13{,}5 \pm 2{,}8$
60 (40 ÷ 80)	Em [*384*]	$15{,}5 \pm 2{,}3$
65 (0 ÷ 130)	Em [*375*]	6 ± 4
70 (60 ÷ 80)	P-BC [*363*]	$12{,}8 \pm 3{,}0$
80 (50 ÷ 110)	Em [*376*]	27 ± 8
80 (60 ÷ 100)	Em [*370*]	14 ± 3
85 (80 ÷ 90)	P-BC [*363*]	$11{,}0 \pm 3{,}3$
93	Em [*366*]	$14{,}7 \pm 1{,}7$
100 (50 ÷ 150)	Em [*371*]	14 ± 3
100 (40 ÷ 160)	Em [*372*]	$14{,}6 \pm 3{,}3$
110 (40 ÷ 150)	Em [*380*]	12 ± 4
120 (60 ÷ 180)	Em [*381*]	$14{,}5 \pm 2{,}2$
120 (80 ÷ 160)	Em [*384*]	$15{,}5 \pm 2{,}3$
125	Em [*369*]	15
150 (100 ÷ 200)	Em [*365, 367*]	$14{,}2 \pm 2{,}6$
175	C [*368*]	$16{,}3 \pm 1{,}7$
175	C [*362*]	$16{,}4 \pm 1{,}4$
180 (140 ÷ 218)	Em [*383*]	15 ± 6
192	C [*382*]	$15{,}4 \pm 3{,}0$
225	C [*368*]	$15{,}2 \pm 1{,}3$
225	C [*362*]	$14{,}6 \pm 1{,}2$
227	Em [*366*]	$14{,}7 \pm 1{,}7$
250 (200 ÷ 300)	Em [367]	$18{,}0 \pm 3{,}5$
261 (200 ÷ 350)	Em [*373,378*]	24^{+8}_{-7}
270 (240 ÷ 300)	Em [*374*]	17
270 (200 ÷ 350)	Em [*377*]	$21{,}3 \pm 4{,}5$
270 (200 ÷ 350)	Em [*365*]	$21{,}3 \pm 4{,}5$
275	C [*368*]	$16{,}3 \pm 1{,}7$
275	C [*362*]	$15{,}6 \pm 1{,}4$
304	Em [*379*]	$21{,}6 \pm 6{,}5$
456	H-BC [*385*]	$16{,}0 \pm 1{,}4$
600	C [*338*]	$17{,}5 \pm 1{,}5$
700	C [*338*]	$19{,}6 \pm 1{,}2$
960	C [*338*]	$18{,}8 \pm 0{,}8$
1,1 Bev	C [*338*]	$16{,}4 \pm 0{,}7$
1,23	C [*338*]	$18{,}3 \pm 0{,}8$
1,45	C [*338*]	$15{,}7 \pm 0{,}7$
1,6	C [*338*]	$15{,}5 \pm 1{,}1$
1,95	C [*338*]	13 ± 1
2,3	C [*452*]	$15{,}0 \pm 2{,}1$
2,45	C [*359*]	$23{,}8 \pm 2{,}5$
2,45	C [*452*]	$17{,}4 \pm 1{,}7$
2,9	C [*452*]	$18{,}6 \pm 1{,}6$
3,09	C [*359*]	$23{,}2 \pm 2{,}0$
3,24	C [*311*]	$21 \pm 4{,}3$
3,26	C [*452*]	$20{,}5 \pm 1{,}6$
4,28	C [*311*]	$21{,}3 \pm 4{,}6$
4,33	C [*452*]	$25{,}8 \pm 2{,}7$
4,43	C [*359*]	$19{,}7 \pm 1{,}4$
7,42	C [*359*]	$19{,}4 \pm 0{,}8$

---

*) Calculated by the experimental values of the scattering lengths (see 3.1).

At $T = 280$ Mev, the estimate $\sigma_{in}(K^+N) \simeq 0{,}15$ mb [*389*] has been obtained from the interaction with emulsion nuclei.

Table XVII. K^+n interaction

T	method	σ_{el} [mb]	σ_{ex} [mb]	σ_t [mb]
0 Mev	*)	$3{,}2 \pm 1{,}0$	$4{,}1 \pm 1{,}1$	$7{,}3 \pm 1{,}4$
50 (30 ÷ 60)	Em [*364*]	$8{,}5 \pm 4{,}2$	$2{,}3 \pm 0{,}6$	$10{,}8 \pm 4{,}8$
50	Em [*386*]	—	$0{,}8 \pm 0{,}7$	—
50	Em [*380*]	10 ± 7	$2{,}5 \pm 1{,}0$	$12{,}5 \pm 8{,}1$
52	D-BC [*385*]	—	$0{,}9^{+0{,}7}_{-0{,}3}$	—
54	Em [*387*]	$9{,}2 \pm 7{,}3$	$1{,}2 \pm 0{,}5$	$10{,}4 \pm 7{,}8$
60 (40 ÷ 80)	Em [*384*]	—	—	11 ± 5

Table XVII. (continued)

T	method	σ_{el} [mb]	σ_{ex} [mb]	σ_t [mb]
60	Em *[386]*	—	1,0 ± 0,5	—
65 (0 ÷ 130)	Em *[375]*	4,1 ± 3,8	3,4 ± 1,0	7,5 ± 4,8
70	Em *[386]*	—	1,0 ± 0,8	—
70	Em *[380]*	9,7 ± 4,5	4,4 ± 1,1	14,1 ± 5,6
80 (40 ÷ 120)	Em *[375]*	—	—	2 ± 2
90	Em *[386]*	—	0,8 ± 0,7	—
93	Em *[366]*	7.9 ± 3,1	5,6 ± 1,6	13,5 ± 3,6
95	Em *[387]*		2,7 ± 1,3	10,4 ± 5,2
95	Em *[380]*	11.8 ± 3.8	4,0 ± 1,0	15,4 ± 4,8
100	D-BC *[385]*	—	2,8 ± 0,5	—
100 (40 ÷ 160)	Em *[372]*	—	2,0 ± 0,6	10,4 ± 2,8
110	Em *[380]*	15.2 ± 3.8	3,9 ± 1,0	19,1 ± 4,8
110	Em *[386]*		1,2 ± 0,7	—
117	Em *[386]*		1,5 ± 0,5	
120	Em *[384]*		—	9 ± 3
120 (60 ÷ 180)	Em *[381]*	5.8 ± 3.1	4,0 ± 0,8	9,8 ± 3,0
120 (80 ÷ 150)	Em *[380]*	5,7 ± 1,9	5,7 ± 1,9	11,4 ± 2,8
125 (100 ÷ 150)	Em *[388]*	2,3 ± 4,4	5,2 ± 4,0	13,5 ± 3,6
125	Em *[369]*	5,3 ± 3,8	2,2 ± 1,0	7,5 ± 4,8
127	D-BC *[385]*	—	3,1 ± 0,4	—
130	Em *[380]*	12,1 ± 3,7	5,4 ± 1,1	17,5 ± 4,8
140	Em *[387]*	10,6 ± 4,9	4,3 ± 1,2	14,9 ± 6,1
155	Em *[386]*	—	3,0 ± 1,0	—
165 (118 ÷ 196)	Em *[389]*	12,1 ± 1,6	4,6 ± 1,2	—
175 (150 ÷ 200)	Em *[388]*	1,9 ± 4,9	7,5 ± 4,0	7,0 ± 2,5
175 (100 ÷ 250)	Em *[388]*	1,7 ± 2.5	7,7 ± 2,2	9,4 ± 1,9
180 (140 ÷ 218)	Em *[383]*		—	10,3 ± 3,5
192	Em *[382]*		3,7	7,5 ± 2,1
195	Em *[386]*	—	6,0 ± 1,8	—
225 (200 ÷ 250)	Em *[388]*	1,0 ± 4,3	9,8 ± 4,0	10,2 ± 2,5
227	Em *[366]*	9.1 ± 3.2	7,3 ± 1,7	16,4 ± 3,8
230	D-BC *[385]*	—	5,8 ± 0,6	—
233 (196 ÷ 271)	Em *[389]*	10,5 ± 1.8	9.3 ± 2,2	—
255	Em *[386]*	—	6.0 ± 1,0	—
265	Em *[386]*		11,0 ± 2,0	—
270	Em *[386]*		8,2 ± 1,8	—
285	Em *[386]*		9,0 ± 1,6	—
315	D-BC *[385]*	—	6,7 ± 0,6	—
315 (271 ÷ 359)	Em *[389]*	8,0 ± 1,5	10,3 ± 2,4	—
330	Em *[386]*	—	16,0 ± 3,0	—
600	C *[338]*	—	—	15,6 ± 4,9†
710	C *[338]*	—	—	20,0 ± 2,7†
900	C *[338]*		—	17,7 ± 2,2†
1,2 Bev	C *[338]*		—	18,0 ± 4,0†
1,4	C *[338]*	—	—	19,3 ± 4,2†
1,9	C *[338]*	—	—	13,1 ± 3,7†

---

*) Calculated by the experimental values of the scattering lengths (see 3.1).

Table XVIII. K⁻p interaction

T	method	σ_t [mb]
84 Mev	H-BC [355]	90
89	N [360]	94,6 ± 9,0
140	N [360]	88,6 ± 8,0
140	H-BC [355]	87
223	H-BC [361]	48 ± 4
238 (150 ÷ 300)	Em [341]	107 ± 45
314	H-BC [361]	38 ± 3
412	H-BC [361]	40 ± 2
530	C [340]	52 ± 9
600	C [358]	47,1 ± 1,2
710	C [358]	43,6 ± 1,6
770	H-BC [457]	48 ± 5
830	C [358]	33,8 ± 0,9
940	C [358]	31,2 ± 0,9
960	C [338]	36 ± 5
1,07 BeV	C [338]	32,5 ± 0,8
1,18	C [338]	32,5 ± 0,8
1,23	C [338]	44 ± 5
1,31	C [358]	32,5 ± 0,6
1,52	C [358]	30,5 ± 0,4
2,04	C [358]	26,9 ± 0,5
2,35	C [360]	20 ± 5
2,52	C [358]	25,3 ± 0,4
3,52	C [358]	25,4 ± 0,7
3,68	C [359]	29,6 ± 3,1
4,43	C [359]	26,7 ± 1,4
7,42	C [359]	24,3 ± 1,4

Table XIX. K⁻p interaction

T	method	σ_{el} [mb]
5 Mev	Em [432]	187^{+153}_{-47}
5 (0 ÷ 10)	Em [335]	58,5 ± 33,8
6 (2.5 ÷ 10)	H-BC [337]	70 ± 22
6 (2.5 ÷ 10)	H-BC [354]	36 ± 15
10	Em [432]	105^{+61}_{-31}
11	N [360]	88 ± 17
15 (5 ÷ 25)	Em [350]	57 ± 24
15 (10 ÷ 20)	Em [335]	59,4 ± 18,8
17 (10 ÷ 23)	H-BC [337]	92 ± 15
17 (10 ÷ 23)	H-BC [354]	66 ± 11
20 (10 ÷ 30)	Em [352]	77 ± 15
20 (10 ÷ 30)	Em [335]	56,1 ± 11,6
21 (0 ÷ 30)	Em [346]	49^{+32}_{-19}
22	Em [432]	108 ± 40
25 (20 ÷ 30)	Em [335]	53,9 ± 14,7
29	N [360]	79 ± 10
30 (23 ÷ 40)	H-BC [337]	86 ± 11
30 (23 ÷ 40)	H BC [354]	67 ± 8
30	H-BC [343]	45 ± 30
35 (25 ÷ 45)	Em [350]	56 ± 16
35	Em [341]	76 ± 13
35 (30 ÷ 40)	Em [335]	66,0 ± 14,1
38 (5 ÷ 60)	Em [348]	60^{+11}_{-9}
40	Em [352]	63 ± 10
40	Em [432]	68^{+22}_{-18}
40 (30 ÷ 50)	Em [335]	56,0 ± 8,65
45 (40 ÷ 50)	Em [335]	48,0 ± 10,7
47 (40 ÷ 55)	H-BC [337]	51 ± 13
47 (40 ÷ 55)	H-BC [354]	38 ± 9
47 (30 ÷ 60)	Em [346]	41^{+17}_{-12}
49	N [360]	56 ± 8
52	Em [432]	50^{+20}_{-10}
55 (45 ÷ 65)	Em [360]	40 ± 10
55 (50 ÷ 60)	Em [335]	41,2 ± 9,1
58 (0 ÷ 82)	Em [344]	33^{+13}_{-9}
58 (0 ÷ 82)	Em [346]	37^{+9}_{-8}
60 (50 ÷ 60)	Em [335]	42,4 ± 6,4
60 (50 ÷ 70)	Em [352]	48 ± 8
60 (10 ÷ 100)	Em [351]	45 ± 5
60 (10 ÷ 140)	Em [553]	50 ± 5
65 (30 ÷ 100)	Em [347]	50 ± 5
65 (60 ÷ 70)	Em [335]	43,6 ± 9,9
65	Em [341]	36 ± 7
72 (60 ÷ 82)	Em [346]	30^{+13}_{-10}
75	Em [341]	36 ± 8
75 (70 ÷ 80)	Em [335]	44,9 ± 10
75 (65 ÷ 85)	Em [350]	43 ± 12
76 (5 ÷ 130)	Em [348]	46 ± 6
80 (70 ÷ 90)	Em [352]	38 ± 10
80 (70 ÷ 90)	Em [335]	44,7 ± 9,5
83 (80 ÷ 90)	H-BC [337]	52 ± 7
84	H-BC [355]	52
85 (80 ÷ 90)	Em [335]	44,2 ± 31,3
89	N [360]	62,8 ± 8

Table XIX. (continued)

T	method	σ_{el} [mb]	T	method	σ_{el} [mb]
90	Em [*349*]	$48{,}4\,^{+15}_{-11}$	125 (100 ÷ 150)	Em [*342*]	44 ± 14
90	N [*360*]	31,5 ± 13	140	N [*360*]	50 ± 6
90	Em [*341*]	33 ± 12	140	H-BC [*355*]	43 ± 5
90 (60 ÷ 100)	Em [*348*]	$34\,^{+8}_{-6}$	150 (140 ÷ 160)	H-BC [*337*]	43 ± 5
95 (85 ÷ 105)	Em [*350*]	$13\,^{+130}_{-5}$	238 (150 ÷ 300)	Em [*345*]	40
115 (105 ÷ 125)	Em [*350*]	$33\,^{+33}_{-11}$	238 (150 ÷ 300)	Em [*341*]	35 ± 16
			770	H-BC [*357*]	24,2 ± 4,6
			1500	C [*358*]	7,6 ± 1,5

Table XX. K⁻p interaction

T	method	σ_{ex} [mb]	T	method	σ_{ex} [mb]
< 8 Mev		0	148	H-BC [*336*]	4
18	H-BC [*339*]	11 ± 4	148	H-BC [*339*]	4 ± 2
20 (10 ÷ 30)	Em [*352*]	15 ± 7	238 (150 ÷ 300)	Em [*341*]	5
25	H-BC [*336*]	15	606	C [*358*]	9,0 ± 1,9
34	H-BC [*339*]	17 ± 4	606	C [*358*]	12,9 ± 2,6†
49	H-BC [*339*]	7 ± 3	770	H-BC [*357*]	6,8 ± 1,1
69	H-BC [*339*]	5 ± 3	1,055 Bev	C [*358*]	3,2 ± 0,7
84	H-BC [*355*]	2,5	1,055	C [*358*]	8,0 ± 1,9†
89	H-BC [*339*]	4 ± 3	2	C (*358*]	1,7 ± 0,6
89	N [*360*]	4,1 ± 2,3	2	C [*358*]	1,9 ± 0,3†
140	H-BC [*355*]	5 ± 3	3,49	C [*358*]	5,4 ± 0,9
140	N [*360*]	5,1 ± 2,5	3,49	C [*358*]	1,2 ± 0,6†

Table XXI. K⁻p interaction*)

T	method	σ_{in} [mb]
60 Mev	Em [*353*]	20 ± 5
84	H-BC [*355*]	35 ± 5
89	N [*360*]	28,4 ± 10,9
140	N [*360*]	33,5 ± 9,7
140	H-BC [*355*]	39
238 (150 ÷ 300)	Em [*341*]	67 ± 29
770	H-BC [*357*]	17 ± 3

---

*) Inelastic K⁻p-interaction has no threshold energy.

Table XXII. K⁻n interaction

T	method	σ_t [mb]
600 Mev	C [*358*]	31,2 ± 1,6†
830	C [*358*]	29,4 ± 1,1†
1,07	C [*358*]	26,4 ± 1,0†
1,31	C [*358*]	24,3 ± 0,8†
1,52	C [*358*]	22,7 ± 0,9†
2,04	C [*358*]	22,6 ± 0,9†
2,52	C [*368*]	22,4 ± 0,7†
3,52	C [*358*]	20,5 ± 0,9†

The Tables present the values of the cross sections with account of the corrections for nucleon screening in a deuteron nucleus $I(K^+d)$. These values have been calculated by the Glauber's method. (See Appendix I). The cross sections thus obtained are indicated by the sign †.

As far as the experimental data are known with large errors, most of the curves in Figs. 8 and 9 should be treated only as tentative.

A considerable drop in the magnitude of the cross section $\sigma_t(K^+p)$ has been found in the energy region of about 2 Bev [*338*]. Till most recently it remained quite obscure whether or not his drop can be accounted for. In particular, it was emphasized in [*89*] that the experimental data from [*338*] do not contain the correction for the diffraction scattering, the account of which can make the cross section $\sigma_t(K^+p)$ approximately constant in the range $T > 1$ Bev.

Recent measurements performed at Dubna yielded the values $\sigma_t(K^+p)$ which are consistent close at $T = 2$ Bev with the data of [*338*] and increasing with energy [*452*]. Combined data of [*338, 452*] indicate an existence of the maximum in the cross section $\sigma_t(K^+p)$ in the range of about 800 Mev. The data of [*89, 452*] allow the maximum in the cross section in the energy range of 5 Bev.

The experimental data of [*452*] are fresh, and probably, most accurate. However, we are not brave enough to state that the situation here is quite clear.

The maximum in the cross section $\sigma_t(K^-p)$ at low energies is also not yet quite reliable.

According to the considerations of the charge symmetry and invariance with respect to the charge conjugation, the total cross sections and those for elastic and inelastic interactions must be equal:

$$\sigma(K^+p) = \sigma(K^0n) = \sigma(K^-\bar{p}) = \sigma(\bar{K}^0\bar{n})$$

$$\sigma(K^+n) = \sigma(K^0p) = \sigma(K^-\bar{n}) = \sigma(\bar{K}^0\bar{p})$$

$$\sigma(K^-p) = \sigma(\bar{K}^0n) = \sigma(K^+\bar{p}) = \sigma(K^0\bar{n})$$

$$\sigma(K^-n) = \sigma(\bar{K}^0p) = \sigma(K^+\bar{n}) = \sigma(K^0\bar{p}).$$

Besides,

$$\sigma_{ex}(K^+n) = \sigma_{ex}(K^0p) = \sigma_{ex}(K^-n) = \sigma_{ex}(\bar{K}^0p).$$

At high energies the charge symmetry and invariance with respect to the charge conjugation for K-mesons have not yet been verified. However, they seem to be very likely.

One can see from the above experimental data that the difference between the cross sections for K-meson-proton interaction and those for K-meson-neutron interaction decrease with energy. This points out that the dependence of the interactions on isotopic spin is weakening. At high energies the cross sections for K^+ and K^--meson interaction also become close. The values of these cross sections are approximately two times smaller than those for NN interactions.

2.7 K-Meson Interactions with π- and K-Mesons

At the present time there are some experimental data which points to an existence of a noticeable $K\pi$ interaction. The most important of them are:

1. An analysis of the correlations between K- and π-mesons produced in π^-p collisions at $T = 7$ Bev leads one to the conclusion about the resonance $K\pi$ interaction at $T \simeq 110$ Mev [*390*]. (The $K\pi$ isobar mass $M \simeq 0.8$ Bev [*325*], [*390*].)

2. Λ-hyperons produced in π^-p collisions are flying predominantly in the center-of-mass system in the direction opposite to that of a primary π-meson, while the K-mesons have an approximately symmetrical distribution (somewhat peaked forward, see e.g., [*391*]). Such a character of the angular distributions of strange particles produced at high energies can be understood if we take into account the peripheral collisions of a primary π-meson with the K-meson cloud of a nucleon (cf. 5 in [*392*]). One-meson approximation calculation yields $\sigma(K\pi) \sim \sigma(\pi N)$ for the Kπ interaction cross section. (The numerical results depend on whether the K-meson is assumed to be scalar on pseudoscalar. The latter case is likely to be more preferable).

3. An optical analysis of elastic Kp scattering at high energies points to a considerable probability of Kπ interactions for large impact parameters. For the Kπ interaction cross section an estimation of $\sigma(K\pi) \sim \sigma(\pi N)$ [*393*] also follows from here.

It should be also emphasized that the „*D*-like“ events of πN interactions observed at Dubna and other laboratories may be also interpreted as a result of K- and π-meson interaction.

It is shown in [*403*] and [*404*], that the account of the interaction

$$H_{\text{int}} = \lambda\left(\overline{K}^+K^+ + \overline{K}^0K^0\right)(\pi^+\pi^- + \pi^-\pi^+ + \pi^0\pi^0)$$

where π, K, $\overline{K}$ are the operators of the fields of the corresponding particles, and λ is the coupling constant, enables to explain a number of experimental facts on the K-meson interaction with nucleons and nuclei at low energies. One can show that the charge exchange reaction in this theory $\pi^0 + K^+ \rightarrow \pi^+ K^0$ is forbidden [*394*]. Therefore, in the one-meson approximation the reaction $K^+ + p \rightarrow p + K^0 + \pi^+$ is also forbidden. (See Fig. 10.) To check this conclusion experimentally is of great interest.

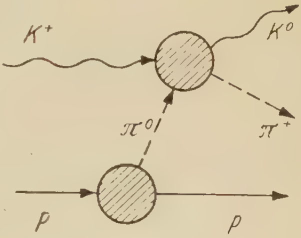

Fig. 10

If the K^+ and K^0 mesons have different parity, then a triple interaction of the kind $H_{\text{int}} = \lambda\overline{K}\pi K$ is possible.

As is seen, the information about Kπ interaction are even poorer than about the interaction of pions.

In the energy region not exceeding some hundred Mev, Isaev and Sewerinski have recently obtained the equations for the amplitude of Kπ interactions [*395*] by using the double dispersion relations. Analogous equations have been got also by B. Lee [*396*]. However, the solution of these equations has not yet been found.

From the theoretical point of view, one can expect an appreciable interaction of K-mesons with K-mesons. (It is likely, that $\sigma(KK) \sim \sigma(K\pi) \sim \sigma(\pi N)$.) However, no experimental data on such an interaction are not available at present. The information on the KK interaction could in particular, be extracted from the study of the angular and energy distribution of strange particles produced in the reactions

$$K + N \rightarrow K + K + \Lambda(\Sigma) + n\pi \quad (n = 0,1\ .\ .\ .).$$

Such interactions may be treated as peripheral collisions of an incident K-meson with the K-meson cloud of a nucleon.

III. Theoretical Interpretation of the Experimental Data

One can see from the experimental data given above that the behaviour of the interaction cross sections is of a very complicated form. Whatever detailed theoretical consideration of this behaviour could be given only in a detailed monograph and would be far beyond a journal's review. Therefore, we restrict ourselves to the consideration of only the limiting cases of very low ($T \gtrsim 10$ Mev) and high ($T \gtrsim 1$ Bev) energies. In these energy regions there are some interesting features which are common for the interaction of different particles.

3.1 On the Behaviour of the Cross Sections at Very Low Energies

To describe the particle interaction at low energies one can make use of the well-developed theory of the effective range [*407*, *412*, *381*].

In the particular case of the slow neutron interaction with protons the cross section for the interaction has the form:

$$\sigma(T) = \frac{3\pi}{K^2 + \left(\frac{1}{a_t} - \frac{K^2}{2}\varrho_t\right)^2} + \frac{\pi}{K^2 + \left(\frac{1}{a_s} - \frac{K^2}{2}\varrho_s\right)^2}$$

where

$$K^2 = \frac{1}{2}\left(\frac{T}{M}\right)\frac{1}{\bar{\lambda}_n^2}.$$

(T/M) is the kinetic energy of a neutron in the units of its mass M, $\bar{\lambda}_n = \hbar/MC$:

$$a_t = (5{,}415 \pm 0{,}012)\,10^{-13}\ \text{cm}; \qquad \varrho_t = 1{,}7\,(1 \pm 0{,}017)\,10^{-13}\ \text{cm}$$

$$a_s = -\,(23{,}806 \pm 0{,}028)\,10^{-13}\ \text{cm}; \qquad \varrho_s = 2{,}5\,(1 \pm 0{,}1)\,10^{-13}\ \text{cm}.$$

The values of these parameters have been determined from the comparison with the experimental cross sections $\sigma(T)$ [*408*]. As is seen from Fig. 1 the experiment and the theory agree well up to the energies of the order of some dozen Mev. At higher energies the form of the nuclear potential is of importance, and a more detailed consideration is necessary.

In case of pp scattering the Coulomb forces are essential. However, the theory of the effective range allows to extracted here the cross section of purely nuclear scattering from the experimental data:

$$\sigma(T) = \frac{\pi}{K^2 + \left(\frac{1}{a_s} - \frac{K^2}{2}\varrho_s\right)^2}.$$

where again $K^2 = \frac{1}{2}\,(T/M)\,1/\bar{\lambda}_n^2$ 9).

The values of the parameters a_s and ϱ_s determined from comparing with experiment are in good agreement with the corressponding values for pn scattering, as it

---

9) For the total wave function to be antisymmetrical, the pp system may have only singlet spin states for the even orbital moments. Therefore, at low energies when scattering takes place in the S-state, the pp system may be in the ^{1}S-state only.

should have been expected from the charge independence considerations [*408*]. The effective range approximation is principally applicable to $\overline{\mathrm{N}}\mathrm{N}$ interactions also. However, in this case the know experimental data are found to be insufficient for an unambiguous determination of the parameter in the formulas for the cross sections: (Note, that these parameters are complex due to the thresholdless inelastic annihilation processes).

In pion scattering on nucleons the P-wave scattering play an essential part. Therefore, the number of the parameters is getting larger, and the formulae for the cross sections have a more complicated form than for nucleon interaction. Within the limit $T \to 0$, when the interaction occurs in the S-state

$$\sigma(\pi^+ p) = 4\pi a_4^2$$

$$\sigma_{\mathrm{el}}(\pi^- p) = \frac{4\pi}{9} (2a_1 + a_3)^2$$

$$\sigma_{\mathrm{ex}}(\pi^- p) = \frac{8\pi}{9} (a_3 - a_1)^2$$

$$\sigma_{\mathrm{t}}(\pi^- p) = \frac{4\pi}{3} (2a_1^2 + a_3^2).$$

It is likely that one of the most exact values of the scattering lengths in the states with the isotopic spins $t = {}^1/_2$ and $t = {}^3/_2$ have been obtained in [*412*]

$$a_1 = (0{,}249 \pm 0{,}007)\ 10^{-13}\ \mathrm{cm}; \qquad a_3 = -(0{,}122 \pm 0{,}007)\ 10^{-13}\ \mathrm{cm}.$$

There are some papers in which the range approximation is applied to the K-meson interaction with nucleons (see, e. g., [*410, 411, 381*], where the bibliography is given). This theory turns out to be very complicated, since, for instance, in case of K^-p interaction the thresholdless inelastic reactions are possible, and the scattering lenghts become complex [*411*]. We present here only the values of the scattering lengths for the K⁺N interactions [*381*] (the details are given in the references)

$$\sigma(\mathrm{K}^+ p) = 4\pi a_1^2$$

$$\sigma_{\mathrm{el}}(\mathrm{K}^+ n) = \pi(a_1 + a_0)^2$$

$$\sigma_{\mathrm{ex}}(\mathrm{K}^+ n) = \pi(a_1 - a_0)^2$$

$$\sigma_{\mathrm{t}}(\mathrm{K}^+ n) = 2\pi(a_0^2 + a_1^2)$$

where $a_1 = -(0{,}336 \pm 0{,}028)\ 10^{-13}$ cm; $a_0 = (0{,}020 \pm 0{,}042)\ 10^{-13}$ cm are the scattering lengths in the triplet and singlet isotopic states.

The corresponding values of the cross sections at $T = 0$ are indicated in the Tables of the previous section.

3.2 On Constancy of Interaction Cross Sections at High Energies

It can be seen from the above experimental data that the cross sections σ_{t}, σ_{in}, σ_{el} are becoming constant at high energies. However, the data obtained from the cosmic ray experiments at very high energies contain large errors and strictly speaking, one can only say that at these energies the magnitude of the interaction cross section does not considerably change.

At the present time there is no theory which would account for the behaviour of the cross sections even at those high energies which are available in the modern experiment. Moreover, the constancy in the interaction cross sections at $T \gg 1$ Bev seems to be contradictory to the modern field theory, where in calculating many physical quantities (particle masses, magnetic moments etc) one has to introduce the form-factors to suppress the interactions at high energies. However, examplex can be given (see e. g., 3.3), when even very weak interactions lead to large values of the cross sections with energy. The suppression of the interactions with the aid of the form-factors may in this case compensate the increase of the cross sections and make them constant. Probably an analogous situation takes place in the general case as well.

For the energy depedence of the cross sections for pion interaction with nucleous, the boundary estimates

$$\frac{\text{const}}{T} < \sigma_t(T) < T \cdot \text{Const}$$

have been obtained in [*413*] from the analysis of the properties of the expansion functions in the local field theory. These estimates are not in disagreement with the experimental data. More definite conculsions about the asymptotic behaviour of the cross sections have been made in papers [*414*, *415*] recently published. It has been found in these papers from the consideration of inelastic peripheral interactions at high energies by using the one-meson approximation are that $\sigma(T)$ decreasing with energy:

$$\sigma(T) \leq \frac{\text{const}}{\ln T} \quad \text{at} \quad T \to \infty.$$

An analogous conclusion was obtained in [*416*] by means of dispersion relations. As far as the cross sections are getting smaller very slowly (with the energy increase from 1 Bev up to 10^4 Bev the cross section decreases approximately by 10% [*416*]), this does not contradict the known experimental data.

However, the conclusions of papers [*414*—*416*] are based on a number of assumptions and are not convincing enough. So, in papers [*414*, *415*] the interaction in which one of the interacting particles is *virtual* is replaced by the interaction of *real* particles. It is possible that such a replacement is correct only up to comparatively slowly changing logarithmic terms which just compensate the logarithmic decrease of the cross sections. One can give the examplex of mathematical expressions when a similar situation takes place. At any rate, this problem requires a special consideration[10]). At present one can only say that the interesting results obtained in papers [*414*—*416*] point out that it is necessary to be very careful in extrapolating the methods of calculations to the region of extremely high energies.

3.3 The Equality of the Cross Sections for Particle and Antiparticle Interactions

It is possible to prove that the total cross sections for (pp) and ($\bar{p}$p) interactions are equal by assuming that the cross sections for proton-proton and proton-antiproton interaction are constant at high energies. The same holds for the total cross sections for π^-- and π^+-meson interaction with protons, for the total cross sections for K$^+$p and K$^-$p interactions etc. — in the general for the interactions in which either a particle participates or — the other time — the respective antiparticle [*417*].

---

[10]) The authors are grateful to D. I. BLOKHINTSEV for a detailed discussion of these problems.

In order to prove this theorem, we consider the dispersion relation for the amplitude of elastic scattering $A(E)$ at the angle $\theta = 0$

$$\operatorname{Re} A(E) = \frac{(E - E_0)^2}{4\pi^2}\, p \int_0^\infty \frac{dE'}{\lambda'} \left[\frac{\sigma_t(E')}{(E' - E)(E' - E_0)^2} + \right.$$

$$\left. + \frac{\bar{\sigma}_t(E')}{(E' + E)(E' + E_0)^2}\right] + a + bE$$

where a and b are the constant coefficients [*418*], λ is the nucleon wave length, $E = T + M$. E_0 is the value of the energy arbitrarily chosen11). It is essential that both the cross section for the particle interaction σ_t and that for antiparticle one $\bar{\sigma}_t$ always enter the dispersion integral.

Keeping only the largest terms we get for $E \to \infty$

$$\operatorname{Re} A(E) \sim E^2 p \int_\varepsilon^\infty \frac{dE'}{E'} \left[\frac{\sigma_t(E')}{E' - E} + \frac{\bar{\sigma}_t(E')}{E' + E}\right]$$

where the value of the energy ε is chosen so that $\varepsilon \gg E_0$ and for $E' \geq \varepsilon$

$$\sigma_t(E') = \sigma_t(\infty); \qquad \bar{\sigma}_t(E') = \bar{\sigma}_t(\infty).$$

After the integral had been calculated

$$\operatorname{Re} A(E) \sim E \ln E\,[\bar{\sigma}_t(\infty) - \sigma_t(\infty)]. \tag{1}$$

However, the elastic scattering amplitude $A(E)$ cannot increase as $E \ln E$. Indeed, at high energies when the harmonics with $l \gg 1$ play the main role

$$|A(E)| = \left|\frac{\lambda}{2} \sum_{l=0}^{\infty} (2l + 1)(1 - e^{2i\eta_l})\right| \leq \frac{1}{\lambda} \int_0^\infty \varrho\, d\varrho\, |(1 - e^{2i\eta(\varrho/\lambda)})| \leq E \cdot \mathrm{Const} \tag{2}$$

since $1/\lambda \sim E$, $\eta \simeq 0$ for $\varrho > R$, where R is the radius of the nuclear forces; and $|(1 - e^{2i\eta(\nu/\lambda)})| < 2$ (cf. [*401*]).

---

11) For the sake of simplicity we shall not take into account the spin and isotopic dependence in the amplitude $A(E)$; all the considerations can be also easily repeated in the general case. We are not going to sonsider the electromagnetic interaction, the account of which introduces only small corrections.

Evidently, relations (1) and (2) are not contradictary, only if

$$\sigma_t(\infty) = \bar{\sigma}_t(\infty). \tag{3}$$

It is shown in paper [*419*], that the difference between the cross sections $\sigma_t(E) - \bar{\sigma}_t(E)$ at $E \to \infty$ is decreasing not slower than $1/\ln E$. Still stronger relation has been obtained in [*420*][12]

$$\sigma_t(E) - \bar{\sigma}_t(E) \leq \text{Const}/E \tag{4}$$

Sometimes it is asserted that the considered limiting relations for the cross sections are the consequence of only the properties of dispersion relations. However, we can see from the proof of relation (3) that these limiting relations have been obtained under the *equivalent assumption* about the constancy of the interaction cross sections at $T \to \infty$. On the contrary, if relation (3) or (4) is considered as the basic one, then from the dispersion relations we get that the constancy of the cross sections at $T \to \infty$.

If the deviations from the constant values of the cross sections, e.g., slow decreasing, as it is predicted in [*414—416*], will occur only at extremely high energies $T \gg (100 - 1000)$ Bev, then in the region of lower energies this will give only small corrections to the dispersion relations, and all the considerations mentioned-above, and equality (3) particularly, will remain approximately correct at energies $T \lesssim (100 - 1000)$ Bev.

3.4 Dependence of Interactions on Isotopic Spins

At $T \lesssim 1$ Bev particle interactions depend essentially on their isotopic spins. This is seen from the experimental data given above. In Figs. 11 and 12 is shown, as an example, the energy dependence of the experimental π-meson and nucleon interaction cross sections for the states with definite values of the isotopic spin.

However, the number of possible channels of inelastic reactions quickly increases with energy, while the total cross section for inelastic reactions $\sigma_{in} \to$ Const or, at any rate, it does not increase.

The cross section of each of inelastic channels including the channel of charge exchange scattering σ_{ex} becomes still smaller and smaller $\sigma_{ex}/\sigma_{in} \to 0$[13]. In other words, the contribution of the interactions connected with the reorientation of the isotopic spins of the colliding particles becomes negligibly small. This leads to the fact that at high energies the cross section becomes independent of the isotopic spins.

This can be illustrated by the pion and nucleon scattering on nucleons [*422*]: If F_1 and F_3 are the amplitudes of the pion-proton scattering in the states with the isotopic spin $t = \frac{1}{2}$ and $t = \frac{3}{2}$, then the differential cross sections for pion scattering are written as

---

[12] This formula has been obtained from the asymptotic expansion in E degrees of the dispersion relation for the squared amplitude. It was assumed that $\operatorname{Re} A(E) + \operatorname{Re} \bar{A}(E) \to$ $\to$ Const. by $E \to \infty$.

[13] At the same time, it is assumed, of course, that the charge exchange cross section has no resonant character at high energies. This is in agreement with the modern ideas about the mechanism of particle interaction at energies $T \gg 1$ Bev [*401, 421*].

$$
\begin{aligned}
\sigma_1 &\equiv \sigma(\pi^+ p \to \pi^+ p) = |F_3|^2\\
\sigma_2 &\equiv \sigma(\pi^0 p \to \pi^0 p) = \tfrac{1}{9}\,|2F_3 + F_1|^2\\
\sigma_3 &\equiv \sigma(\pi^0 p \to \pi^+ n) = \tfrac{2}{9}\,|F_3 - F_1|^2\\
\sigma_4 &\equiv \sigma(\pi^- p \to \pi^- p) = \tfrac{1}{9}\,|F_3 + 2F_1|^2\\
\sigma_5 &\equiv \sigma(\pi^- p \to \pi^0 n) = \sigma_3 .
\end{aligned}
$$

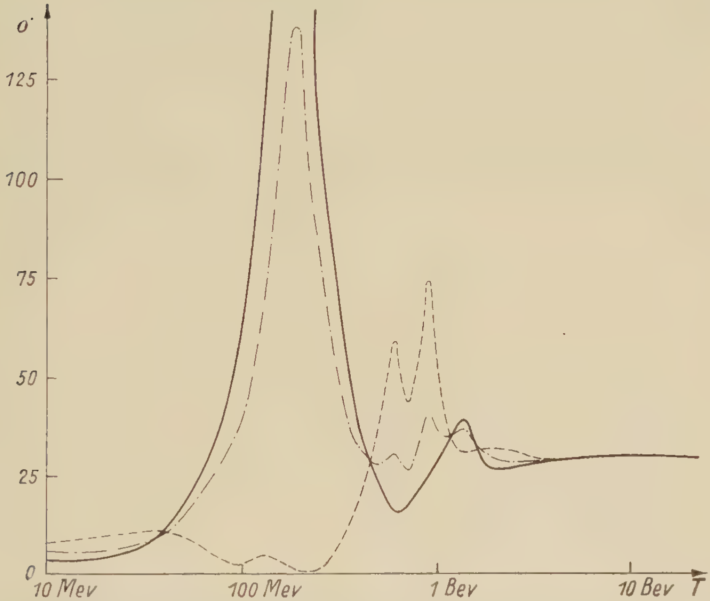

Fig. 11. Total cross sections for π-meson interaction with nucleons in the state with the isotopic spin $t = 3/2$ (solid curve) and in the state with the isotopic spin $t = 1/2$ (dashed line). The dash-dot line the corresponding cross section $\sigma_t(\pi^0 p)$. The values of the cross sections are given in the units of 10^{-27} cm^2.

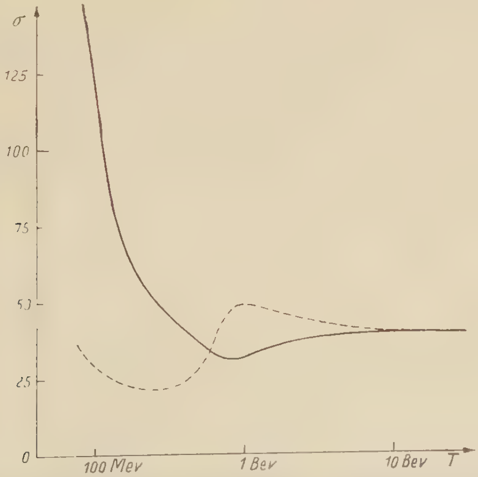

Fig. 12. Total cross sections for nucleon-nucleon interaction in the state with the isotopic spin $T = 0$ (solid curve) and in the state with the isotopic spin $T = 1$ (dashed line). The values of the cross sections are given in the units of 10^{-27} cm.

It follows from the condition of vanishing the charge exchange cross sections $\sigma_3 = \sigma_5 = 0$ that $F_1 = F_3$, i. e.

$$\sigma_1 \simeq \sigma_2 \simeq \sigma_4. \tag{5}$$

As is seen from Figs. 5 and 6 within experimental error the cross sections become independent of the isotopic spins, already at energies $(3 \div 4)$ Bev.

As long as at high energies equality (5) is fulfilled for any scattering angle θ, then the corresponding phases η_e of the scattering amplitude turn out to be equal[14])

$$A(\theta) = \frac{\lambda}{2i} \sum_{l=0}^{\infty} (2l + 1)\,(1 - e^{2i\eta_l})\, P_e(\mathrm{Cos}\,\theta).$$

Hence, the cross sections σ_{in} and σ_{t} are equal.

In case of proton-nucleon scattering the differential cross sections may be written in the form

$$\sigma_1 \equiv \sigma(\mathrm{pp} \to \mathrm{pp}) = |F_1|^2$$

$$\sigma_2 \equiv \sigma(\mathrm{pn} \to \mathrm{pn}) = \tfrac{1}{4}\,|F_1 + F_0|^2$$

$$\sigma_3 \equiv \sigma(\mathrm{pn} \to \mathrm{np}) = \tfrac{1}{4}\,|F_1 - F_0|^2$$

where F_1 and F_0 are the scattering amplitudes in the states with the isotopic spin $t = 1$ and $t = 0$.

It follows from the condition $\sigma_3 = 0$ that $F_1 \simeq F_0$, i. e., $\sigma_1 \simeq \sigma_2$.

Equal are becoming also the phases of the elastic scattering amplitudes η_e and, hence, the cross sections σ_{in} and σ_{t}.

If can be seen from Figs. 2 and 3 that at $T > (5 \div 6)$ Bev the interaction cross section within the experimental accuracy are very weakly dependent on the isotopic spins.

By analogy one can consider the interaction of particles of other kinds. In all cases at high energies the cross sections are very weakly dependent on the isotopic spin.

3.5 Dependence of Interactions on Spins of Colliding Particles

At high energies where the orbital numbers $l \gg 1$ play the main part, the phase of the elastic scattering amplitude depends only on the energy and on the total spin of the colliding particles S, since

$$J = |l - S|; \ldots; |l + S| \simeq l \quad \text{and} \quad l' = |J - S|; \ldots; |J + S| \simeq J \simeq l$$

$$\eta_{ee'}(E, J, S) \simeq \eta_e(E, S).$$

---

[14]) One can become easily sure of this, if equality (5) is rewritten for the scattering amplitudes, multiplied it by a Legendre polynomial and integrated over all the values of Cos from -1 up to $+1$.

Strictly speaking, the statistical speculations about the vanishing of the charge exchange cross sections given above are not applicable in the region of very small angles $\theta \sim 0^0$, where distinct peripheral collisions with a small energy transfer, give the contribution, and the number of inelastic channels is not great. However, with energy the contribution of such interactions decreases quickly.

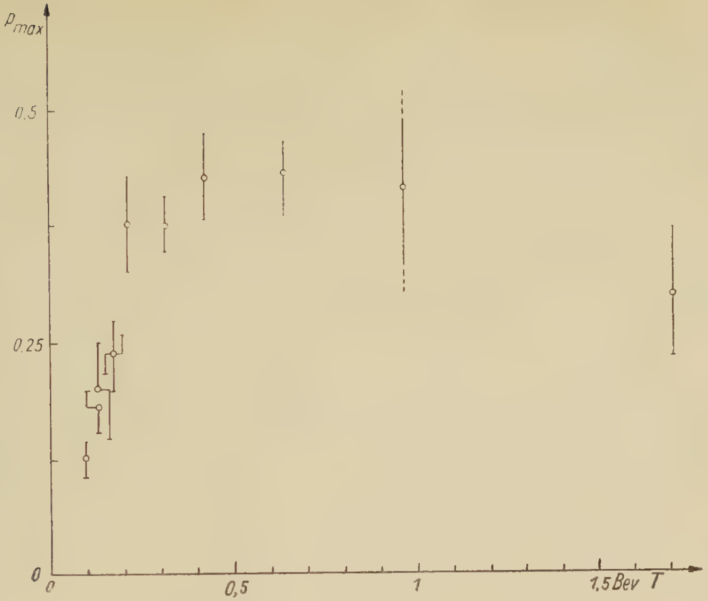

Fig. 13. Maximum polarization in pp interactions.

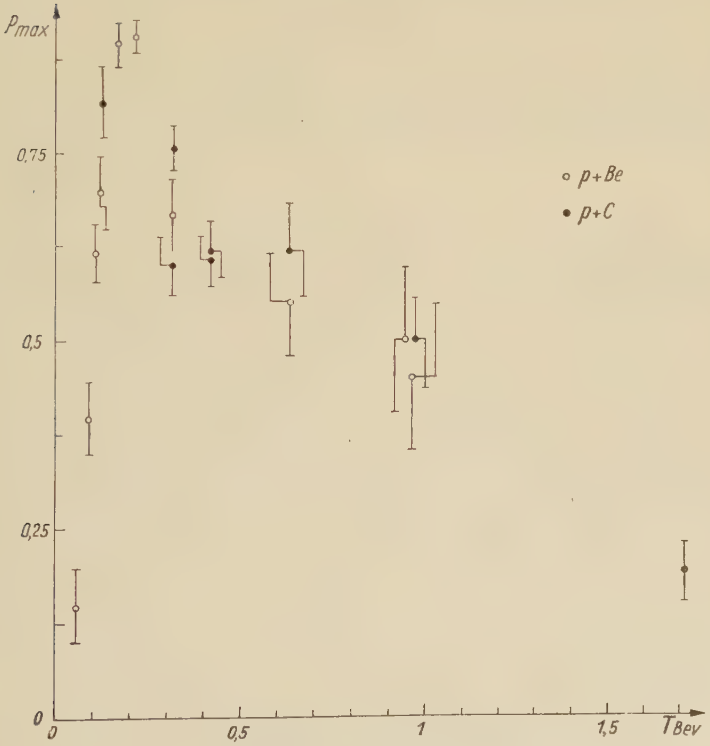

Fig. 14. Maximum polarisation in nucleon interaction with atomic nuclei.

As the recent experiments have shown, in the energy region $T \sim 1$ Bev a noticeable spin dependence of the interactions [*438*] is still observed. This is seen, e. g., from Figs. 13 and 14, where are indicated the experimental values of the maximum magnitude of the polarization in nucleon-nucleon and nucleon-nucleus interactions at different energies. At high energies we have no direct experimental information about the spin dependence of the interactions. However, one can expect that this dependence at energies $T \gg 1$ Bev will be unessential[15]. In case of the interaction between particles of different kinds (for instance, π- or K-mesons with nucleons) this may be accounted for the same reasons as for the isotopic spins. The spin-flip cross section σ_s will quickly decrease in this case with energy.

Such considerations are not applicable to the nucleon-nucleon interactions where there are no transitions between the singlet and triplet states and therefore $\sigma_s = 0$[16]. However, from the standpoint of the modern ideas about the mechanism of inelastic interactions at high energies (the compound-particle model [*423*], the statistical theory of the central and peripheral collisions [*401, 421*]) it may be expected that in this case $\eta_e(E, S) = \eta_e(E)$ as well. (Let us remind that at $T \gtrsim 1$ Bev $\sigma_{el} \simeq \sigma_d$ and are complately determined by inelastic processes.) It stands to reason that all the considerations about the spin and isotopic dependences are applicable to the nuclear interactions as well.

We can see from Figs. 13 and 14 that at high energies the experimental values of the polarization decrease with T, this decreasing being quicker in nucleon-nucleus interactions.

3.6 Weak Interactions at High Energies

Recently the attention of many physicists has been drawn to possible experiments with high energy neutrinos (see, e. g., [*7*] where there is a bibliography). Under usual conditions the neutrino interactions are waek, the cross sections for such interactions are much smaller than those for electromagnetic and nuclear interactions. However, some years ago D. I. Blokhintsev pointed out that at high energies the cross sections for ,,weak interactions" rise fast [*424*]. This was also emphasized by M. A. Markov [*425*].

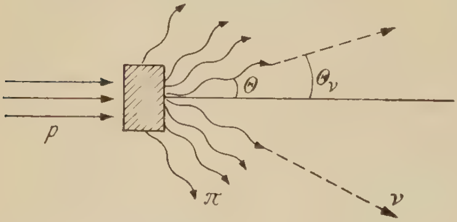

Fig. 15. Neutrino generation by a beam of fast protons.

After powerful proton accelerators were started up, real conditions are created for arranging experiments with high energy neutrinos. In this case the neutrinos appear in the decay of charged pions produced in the collisions of fast nucleons (see Fig. 15). The estimates have shown that in the flux of 10^{11} protons per second at an energy $T = 10$ Bev it is possible to get a neutrino current with energies $T > 1$ Bev $\sim 10^3/\text{cm}^2$ at a distance of 50 m from the target [*426, 427*]. When the distance from the target is increased as much as two times, the neutrino flux increases almost three times. (These data are referred to the small angle region $\theta \sim 0^0 - 3^0$.)

---

[15] Preliminary results of measurements in emulsion at $T = 9$ Bev gave the magnitude of the polarization in pp interaction $p = 0.34 \pm 0.36$ for the angle $\theta = 15.4^0 \pm 2^0$ in the c. m. s. [*94*].

[16] For pp interactions (like for the interaction of any two identical particles). $\sigma_S = 0$ in virtue of the parity conservation low in the system of identical particles; in case of pn interactions $\sigma_S = 0$ owing to the charge symmetry.

As the calculations have shown (see, e. g., [*426*]) the cross sections for neutrino interactions with nucleons and electrons at $T > 1$ Bev are equal to:

$$\sigma(\nu + n \to e + p) = 1.4\,(T/M) \cdot 10^{-38}\ \text{cm}^2.$$

$$\sigma(\bar{\nu} + p \to \bar{e} + n) = 4.8\,(T/M) \cdot 10^{-39}\ \text{cm}^2.$$

$$\sigma(\nu + e \to \nu + e) = 7.8\,(T/M) \cdot 10^{-42}\ \text{cm}^2.$$

$$\sigma(\bar{\nu} + e \to \bar{\nu} + e) = 2.6\,(T/M) \cdot 10^{-42}\ \text{cm}^2.$$

$$\sigma(\bar{\nu} + e \to n + \bar{p}) = 2.6\,(T/M) \cdot 10^{-42}\ \text{cm}^2.$$

where (T/M) is the neutrino (antineutrino) energy in the units of the nucleon mass M; $\bar{\nu}$-antineutrino, $\bar{e}$-positron. These values have been obtained by means of the perturbation theory which is valid up to $T \sim 10^{13}$ Bev. At such gigantic energies the cross sections for neutrino interaction with nucleons are $\sigma \sim 10^{-26}$ cm², i. e., of the same magnitude as the nuclear πN and NN cross sections. However, at high energies the cross sections for νN interactions are essentially modified by the form-factor which take into account the spatial nucleon dimensions. (The application of not quite lawful extrapolation of the Hofstadter from-factor in the region of very high energies leads to the constant cross section $\sigma \sim 10^{-38}$ cm² [*427*]). The same is true for νe interactions (it can be expected that the electron has a geometric dimensions $\sim 10^{-16}$ cm [*429*]).

To check the theory experimentally in the energy region $T \sim 10^{+13}$ Bev it is necessary to have the counter beams of particles with $T \sim 100$ Bev. Recently M. A. Markov paid his attention to an interesting possibility of using the cosmic neutrinos of very high energies [*430*].

VI. Conclusion

The theoretical and experimental data described above may give one a qualitative picture of the behaviour of the cross sections for nucleon, antinucleon, π- and K-meson interactions with nucleons in the energy range of some dozen Bev.

However, in many cases the quantitative data are still insufficient. Especially, this is true for the interaction of antineucleons and K-mesons with nucleons. The interactions with neutrons at high energies is also little investigated. We know practically nothing about the interaction of polarized particles. More accurate measurements are of its own interest here, and are also important for a quantitative check of theoretical schemes and models. It is clear that any information pertaining to $\pi\pi$ interaction, π and K-meson interactions, hyperon interactions is of great interest.

It is likely, the qualitative picture remains the same further in the energy range of some hundred Bev.

At any rate one can point to two problems the investigation of which at high energies is of principal interest. The first one is to investigate how far at $T \to \infty$ the cross sections σ_t, σ_{in}, σ_{el} remain constant. If this constancy, as the experiment predicts now, is conserved up to very high energies, then in the collision of super high energy particles the showers may be formed where the mass of the newly produced particles amy become macroscopic. Figuratively speaking, in this case stars may be created not in the sense as they are understood in the emulsion laboratory but as they are understood by astronomers [*431*].

If it turns out that at high energies the interaction cross sections are decreasing and vanishing, it points to serions difficulties on the way of investigating very small space-time intervals. At high energies the particles will be in this case ,,transparent".

One can hardly say which one of the two possibilities is more interesting.

In the region of very high energies the information about the cross section σ_t may be extracted from the analysis of the mean-free paths of the cosmic rays in the emulsion (see Appendix II). The value of the primary particle energy may be estimated here by the angular distribution of secondary particles with the aid of the well-known formula of C. Castagnoli. When the statisfies is insufficient it is possible to get the conclusions about the magnitude of σ_t within narrow energy intervals.

Another problem of principle is to investigate a possible violation of the equality between the cross sections for particle and antiparticle interactions $\sigma = \bar{\sigma}$. Under the condition that the interaction cross sections remain constant at high energies, such violations would point out that dispersion relations and their basic principles are not valid (in the first turn, the causality principle) in the small regions of space-time.

The only source of information on the interaction of superhigh energy particles is now and very likely to be in the near future the cosmic — ray experiments. Strong hopes are set on the acceleratirs with counter beams. Two counter beams of particles with an energy T enable to investigate the interactions at energies T^2 [*2*].

Appendix I

Nucleon Screening in a Deuterium Nucleus

In most of the cases the cross sections for the interaction of different particles with neutrons are determined by the difference method from the experiments with hydrogen and deuterium. However, due to the mutual screening of nucleons in a deuterium nucleus the cross section for the interaction with a deuteron is not equal to the sum of the cross sections for the interaction with a proton and a neutron $\sigma_d \neq \sigma_p + \sigma_n$. Therefore, in the course of analysing the experimental data it is necessary to introduce the corresponding correction for screening. This correction is very small at low energies, when de-Broglie wavelength of incident particles is large, and there is practically no shadow because of the diffraction scattering of these particles. At high energies, on the contrary, the approximation of the geometric optics is applicable and the screening effect is expressed very vividly (see Fig. 16). In this case thescreening is displaced the stronger, the larger is the cross section for inelastic interaction σ_{in}.

It has been shown by Glauber in ref. [*13*], that with account of screening the imaginary part of the elastic scattering amplitude at zero angle may be put as

$$\mathrm{Im} F_d(0) = \mathrm{Im} F_p(0) + \mathrm{Im} F_n(0) + \lambda \mathrm{Re}[F_p(0) \cdot F_n(0)] \langle r^{-2} \rangle_d \quad (1)$$

where F_d, F_p and F_n are the corresponding amplitudes of elastic particle scattering on a deuteron, proten and neutron; $\langle r^{-2} \rangle_d$ is the mean value of the inverse squared distance between the proton and the neutron in a deuteron; λ is the wavelength of the scatteres particle.

By using the optical theorem, relation (1) may be written as

$$\sigma_d = \sigma_p + \sigma_n + \tfrac{1}{4}\pi \{(4\pi\lambda)^2 \operatorname{Re} F_p(0) \cdot \operatorname{Re} F_n(0) - \sigma_p \sigma_n\} \langle r^{-2} \rangle_d \qquad (2)$$

where σ_d, σ_p and σ_n are the total cross sections for the interaction of an incident particle with a deuteron, proton and a neutron [*13*].

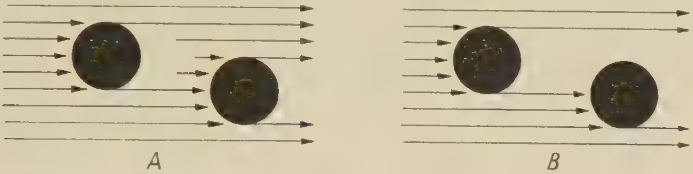

Fig. 16. Screening effect in a deuterium nucleus.
a) The case of low energies. The mean distance between the nucleons L is longer than the dimensions of the shadow region: $L > R/\lambda$.
b) The case of high energies. The mean distance between the nucleons L is shorter than the dimension of the shadow region : $L < R/\lambda$; $R = 10^{-13}$ cm – effective dimensions of a nucleon; λ is the wavelength of an incident particle. For simplicity the case of the black (absolutely absorbing) nucleon is considered.

If the real parts of the amplitude $F_p(0)$ and $F_n(0)$ are neglected in comparison with their imaginary parts, then (2) may be written in a form convenient for the calculations:

$$\sigma_n = \eta(\sigma_d - \sigma_p)$$

$$\eta = \left[1 - \frac{\langle r^{-2} \rangle_d \cdot \sigma_p}{4\pi}\right]^{-1}. \qquad (3)$$

The neglect of the real parts of the amplitudes F_p and F_n is a good approximation at $T \gtrsim 1$ Bev [*401, 444*]. For lower energies – this is a very rough approximation. Below the threshold for inelastic reactions the imaginary parts of the amplitudes are vanishing at all and $F = \operatorname{Re} F$. However, as is seen from formula (2), at low energies the screening effect itself is insignificant. Besides, in most of the cases the values $\operatorname{Re} F_p(0)$ and $\operatorname{Re} F_n(0)$ at $T < 1$ Bev are, all the same, unknown now [*444*].

The value of $\langle r^{-2} \rangle_d$ may be determined if the values of the cross sections σ_d, σ_p, σ_n are known at the same energy from independent measurements. The magnitude of $\langle r^{-2} \rangle_d$ can be calculated purely theoretically also, if the wave function of a deuteron is known. The results of the calculations are somewhat changing depending on a concrete choise of this function. On the average $\langle r^{-2} \rangle_d \simeq 4{,}6 \cdot 10^{25}$ cm^2.

At high energies the cross sections are very weakly energy dependent. In this case the correlation factor η becomes constant and is equal approximately to 0.1 – 0.2. The corresponding correction to the cross section $\sigma_n' - \sigma_d - \sigma_p$ makes up about 20% or less. Below the threshold for inelastic reactions $\eta \simeq 1$ and $\sigma_n = \sigma_d - \sigma_p$. In the intermediate region the calculation of the screening correction is a complicated problem. Appoximately one can may think that in this region η is chaning linearly with energy [*72*].

As we see, the screening corrections are calculated very roughly. In more accurate calculations, one should, in particular, take into account the double scattering in a deuteron nucleus. However, within the experimental error $\pm\delta\sigma$ such an approach is quite satisfactory in the practical calculations of σ_n. The cross sections σ_n thus obtained agree well with the values got from direct measurements in a neutron beam.

Appendix II

Mean-Free Path of High Energy Particles in Emulsions

In analysing the tracks of high energy particles in emulsion the elastic scattering events of these particles on nuclei are not usually fixed. This scattering at high energies is almost completely diffractional and occurs at very small angles which are the smaller, the larger the dimensions of a nucleus. Special methods are necessary in order to fix small distortion of tracks in elastic nuclear scattering.

In all the cases of nucleon and pion interaction with emulsion nuclei, for which the values of the mean free paths are presented in Tables VI and XIV, we took into account, besides inelastic interactions, only elastic scattering on hydrogen at comparatively large angles[17]). The maen free path in these cases is equal to

$$L = \left\{\sum_i N_i \sigma_{\text{in}}^{(i)} + N_{\text{H}}\sigma_{\text{t}}\right\}^{-1} \tag{1}$$

where N_{H} is the number of hydrogen nuclei in 1 cm³ of emulsion;

N_i is the number of nuclei of other elements in 1 cm³ of emulsion (see Table XXIII);

Table XXIII. Emulsion composition (the number of nuclei in 1 cm³; $N_i \cdot 10^{-22}$)

Emulsion	Element					
	H	C	N	O	Br	Ag
Nikfi-p	2,93	1,39	0,37	1,06	1,02	1,02
Ilford G-5	3,37	1,36	0,29	1,02	1,02	1,02

σ_{t} is the total cross section for primary particle interaction with hydrogen;

$\sigma_{\text{in}}^{(i)}$ are the cross sections for inelastic interactions of this particles with other nuclei.

At high energies when the wave length of the particles interacting with emulsion is much smaller than the nuclear dimensions, the optical model can be applied [*401, 435*]:

$$\sigma_{\text{in}}^{(i)} = 2\pi \int_0^\infty r \left[1 - e^{-2k_i \int_0^\infty \varrho_i\left(\sqrt{r^2+s^2}\right) ds}\right] dr. \tag{2}$$

Here

$$\varrho_i(r) = \left\{1 + e^{\left(\frac{r-c_i}{z_i}\right)}\right\}^{-1}$$

---

[17]) Of course, those events of elastic scattering on hydrogen when the particles are flying at very small angles are not fixes either. At energies $T \gtrsim (10 \div 15)$ Bev in (1) σ_{t} should be, strictly speaking substituted by σ_{in}. However, as the estimates show, the contribution of such interactions cannot change appreciably the magnitude of the mean free path.

is the distribution of matter in a nucleus of the i-th kind; the coefficients c_i and z_i are determined in the experiments with fast electron scattering on nuclei [*435*].

The absorption coefficient $k_i = d_i \sigma_t$, where

$$d_i = \frac{A_i}{\int \varrho_i(r) d^3 r}$$

is the mean nucleon density in a nucleus with an atomic number A_i (see Table XXIII).

Formula (2) is correct at $T \gtrsim 1$ Bev. With energy it can be applied better.

The calculated values of L are ploted in Fig. 17 against the magnitude of the cross section σ_t. As the calculations have shown the difference in the paths $L(\sigma_t)$ in the emulsions of Ilford G—5 and NIKFI—P are negligible [*437*]. The curve $L(\sigma_t)$ in Fig. 17 is applicable to both types of emulsion. The values of the cross sections σ_t presented in Tables VI and XIV have been obtained with the aid of this curve.

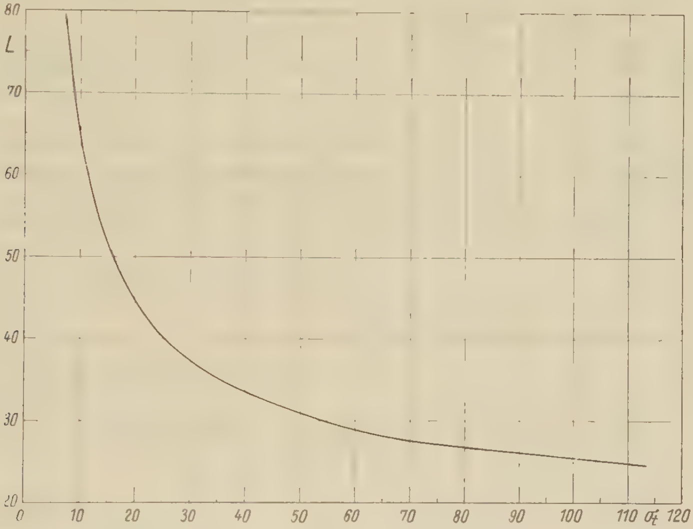

Fig. 17. Mean free path of particles in emulsion L is plotted against the total cross section for the interaction of these particles with nucleons σ_t. The ordinate axis is the values of L in cm; the abscissa axis — the values of the cross section σ_t in the units of 10^{-27} cm^2.

References

[*1*] L. Beretta, C. Villi, R. Ferrari, Suppl. Nouvo Cimento **12**, 499 (1954).

[*2*] V. I. Goldanski, A. L. Lujbimow, B. V. Medvedev, Uspekhi fiz. nauk **48**, 531 (1952); Uspekhi fiz. nauk **49**, 3 (1953).

[*3*] W. N. Hess, Rev. Mod. Phys. **30**, 368 (1958).

[*4*] N. P. Klepikov, V. A. Meshcheryakov, S. N. Sokolov, Preprint of JINR, D-584 (1950).

[*5*] V. S. Barashenkov, Uspekhi fiz. nauk **72**, 53 (1960).

[*6*] V. S. Barashenkov, Preprint of JINR D-630 (1961). (Supplement to review [5]).

[*7*] „On High Energy Neutrino Physics". A collection of papers edited by M. A. Markov; Preprint of JINR D-577 (1960).

[*8*] V. J. Grishin, V. A. Nikitin, M. I. Podgoretsky, Preprint of JINR P-480 (1960).

[*9*] V. A. Nikitin, E. N. Tzyganov, Preprint of JINR D-625 (1960).

[*10*] V. S. Barashenkov, V. M. Maltsev: „Angular distributions of elastic particle scattering"; A Review of Experimental Data (preparad for publication).

[*11*] W. E. Crandall, G. P. Millburn, R. V. Pyll, Phys. Rev. **101**, 329 (1956); W. Birnbaum.

[*12*] A. H. Rosenfeld, R. A. Swanson, S. D. Warshaw, Phys. Rev. **103**, 413 (1956).

[*13*] R. I. Glauber, Phys. Rev. **100**, 242 (1955).

[*14*] H. R. Worthington, I. N. McCruer, D. E. Findley, Phys. Rev. **90**, 899 (1953).

[*15*] J. Rouvina, Phys. Rev. **81**, 593 (1951).

[*16*] R. E. Meagher, Phys. Rev. **78**, 667 (1950).

[*17*] K. B. Mather, Phys. Rev. **82**, 133 (1951).

[*18*] R. O. Bondelid, C. H. Braden, M. E. Vattat, P. Bohlman, Phys. Rev. **87**, 699 (1952).

[*19*] E. J. Zimmerman, P. G. Kruger, Phys. Rev. **83**, 218 (1951).

[*20*] R. O. Kerman, W. E. Kreger, P. G. Kruger, Phys. Rev. **89**, 908 (1953).

[*21*] E. J. Zimmerman, R. O. Kerman, S. Singer, P. G. Kruger, W. Jetschke, Phys. Rev. **96**, 1322 (1954).

[*22*] J. H. Dearnley, C. L. Oxley, J. E. Perry, Phys. Rev. **73**, 1290 (1948).

[*23*] R. R. Wilson, C. E. Creutz, Phys. Rev. **71**, 339 (1947).

[*24*] L. H. Johnston, Yong Su Tsai, Phys. Rev. **115**, 1293 (1959).

[*25*] G. Cvijanovich, B. Dayton, P. Egli, B. Klaiber et al., Preprint CERN (1960).

[*26*] L. H. Johnston, D. E. Young, Phys. Rev. **116**, 989 (1959).

[*27*] D. E. Young, L. H. Johnston, Bull. Amer. Phys. Soc. **4**, 252 (1959).

[*28*] B. Cork, W. Hortsough, Phys. Rev. **94**, 1300 (1954).

[*29*] R. R. Wilson, Phys. Rev. **71**, 384 (1947).

[*30*] F. Faris, B. Wright, Phys. Rev. **79**, 577 (1950).

[*31*] S. Kikuchi, J. Sanada, S. Suwa, J. Hayashi, K. Nisimura, K. Fukunaga, J. Phys. Soc. Japan **15**, 9 (1960).

[*32*] R. R. Wilson, E. J. Lofgren, J. R. Richardson, B. T. Wright, R. S. Shankland, Phys. Rev. **71**, 560 (1947); **72**, 1131 (1947).

[*33*] I. L. Yntema, M. C. White, Phys. Rev. **95**, 1226 (1954).

[*34*] B. Cork, Phys. Rev. **80**, 321 (1950).

[*35*] I. W. Burking, I. R. Richardson, G. E. Schrank, Phys. Rev. **113**, 290 (1959).

[*36*] T. H. Jeong, L. H. Johnston, G. W. Waddell, D. E. Young, Phys. Rev. **118**, 1080 (1959).

[*37*] Yung Su Tsai, L. H. Johnston, Bull. Amer. Phys. Soc. **3**, 204 (1958).

[*38*] W. K. H. Panofsky, F. L. Follmore, Phys. Rev. **79**, 57 (1950).

[*39*] F. L. Fillmore, Phys. Rev. **83**, 1252 (1951).

[*40*] B. Cork, L. H. Johnston, C. Richman, Phys. Rev. **79**, 71 (1950).

[*41*] L. H. Johnston, D. A. Swenson, Phys. Rev. **111**, 212 (1958).

[*42*] V. E. Kruge, J. M. Teem, N. F. Ramsey, Phys. Rev. **94**, 1795 (1954); **101**, 1079 (1956).

[*43*] R. H. Hildebrand, C. Leith, Phys. Rev. **80**, 842 (1950).

[*44*] I. N. Palmieri, Z. M. Cormack, N. F. Ramsey, R. Wilson, Ann. Phys. **5**, 299 (1958).

[*45*] D. E. Young, L. H. Johnston, Phys. Rev. **119**, 313 (1960).

[*46*] B. W. Birge, U. E. Kruse, N. F. Ramsey, Phys. Rev. **83**, 274 (1951).

[*47*] L. I. Cook, E. M. McMillan, I. M. Peterson, D. C. Sewell, Phys. Rev. **75**, 7 (1949).

[*48*] V. Culler, R. W. Waniek, Phys. Rev. **95**, 585 (1954); **99**, 740 (1955).

[*49*] J. De Juren, N. Knable, Phys. Rev. **77**, 606 (1950).

[*50*] A. E. Teylor, E. Wood, L. Bird, Nuclear Phys. **16**, 320 (1960).

[*51*] R. Aphonce, A. Johansson, A. E. Taylor, G. Tibell, Phil. Mag. **46**, 295 (1955).

[52] O. Chanberlain, E. Segré, C. Wiegand, Phys. Rev. **81**, 284 (1951); **83**, 923 (1951).

[53] J. Marshall, L. Marshall, V. A. Nedzel, Phys. Rev. **92**, 834 (1953).

[54] J. Cassels, G. H. Stafford, T. G. Pickvance, Nature **168**, 468 (1951).

[55] I. M. Cassels, T. G. Pickavance, G. H. Stafford, Proc. Roy. Soc. **214**, 262 (1952).

[56] A. E. Taylor, T. G. Pickavance, I. M. Cassels, T. C. Randle, Phil. Mag. **42**, 751 (1951).

[57] C. Caverzasio, A. Michalowicz, J. Phys. Radium **21**, 314 (1960).

[58] E. Lohrman, M. Teucher, M. Schein, Phys. Rev. Lett. **6**, 209 (1961).

[59] A. E. Taylor, Phys. Rev. **92**, 1071 (1953).

[60] O. Chamberlain, I. D. Garrison, Phys. Rev. **95**, 1349 (1954); **103**, 1860 (1956).

[61] H. G. de Carvalho, Phys. Rev. **96**, 398 (1954).

[62] O. Chamberlain, G. Pettengill, E. Segré, C. Wiegand, Phys. Rev. **93**, 1424 (1953).

[63] C. L. Oxley, R. D. Schamberger, Phys. Rev. **85**, 416 (1952).

[64] O. A. Towler, Phys. Rev. **84**, 1262 (1951); **85**, 1024 (1952).

[65] J. de Juren, Phys. Rev. **80**, 27 (1950).

[66] R. Fox, C. Leith, L. Wouters, K. R. MacKenzie, Phys. Rev. **80**, 23 (1950).

[67] A. Ashmore, R. G. Jarvis, D. S. Mather, S. K. Sen, Proc. Phys. Soc. **70**, 745 (1957).

[68] V. P. Dzhelepov, V. I. Satarov, B. M. Golovin, Dokl. Akad. Nauk **104**, 717 (1955).

[69] U. R. Holt, I. C. Kluyver, I. A. Moore, Proc. Phys. Soc. **71**, 770 (1958); **71**, 781 (1958).

[70] I. Marshall, L. Marshall, A. V. Nedzel, Phys. Rev. **91**, 767 (1953).

[71] V. A. Nedzel, Phys. Rev. **94**, 174 (1954).

[72] F. F. Chen, C. P. Leavitt, A. M. Shapiro, Phys. Rev. **103**, 211 (1956); **95**, 663 (1954).

[73] V. P. Dzhelepov, V. I. Moskalev, S. V. Medved', Dokl. Akad. Nauk, **104**, 380 (1955).

[74] L. W. Smith, A. W. McReynolds, G. Snow, Phys. Rev. **97**, 1186 (1955).

[75] N. P. Bogachev, I. K. Vzorov, Dokl. Akad. Nauk **99**, 931 (1954).

[76] M. G. Meshcheryakov, N. P. Bogachev, B. S. Neganov, Izv. Akad. Nauk (SSSR) **19**, 548 (1955).

[77] M. J. Longo, I. A. Helland, W. N. Hess, B. I. Moyer, V. Perez-Mendez, Phys. Rev. Lett. **3**, 568 (1959).

[78] N. E. Booth, G. W. Hutchinson, B. Ledley, Proc. Phys. Soc. **71**, 293 (1958).

[79] T. W. Morris, E. C. Fowler, I. D. Garrison, Phys. Rev. **103**, 1472 (1956).

[80] W. B. Fowler, R. P. Whutt, A. M. Thorndike et al., Phys. Rev. **103**, 1489 (1956).

[81] F. F. Chen, C. P. Leavitt, A. M. Shapiro, Phys. Rev. **103**, 211 (1956).

[82] M. E. Low, G. W. Hutchinson, D. H. White, Nuclear Phys. **9**, 600 (1958/59).

[83] P. I. Duce, W. O. Look, P. V. March et al., Phil. Mag. **2**, 204 (1957).

[84] T. Elioff, L. Agnew, Phys. Rev. Lett. **3**, 285 (1959).

[85] T. Coor, D. A. Hill, W. F. Hornyak, L. W. Smith, G. Snow, Phys. Rev. **98**, 1369 (1955).

[86] B. Cork, W. A. Wentzel, C. W. Causey, Phys. Rev. **107**, 859 (1957).

[87] R. Cester, T. F. Hoang, A. Kernan, Phys. Rev. **103**, 1443 (1956).

[88] V. N. Preston, R. Wilson, I. C. Strut (W. M. Preston's communication in a letter to Tzyganov).

[89] G. von Dardel, D. H. Frisch et al., Proc. of the 10-th International Conference on High Energy Phys. Rochester, 1960. Preprint CERN (1960).

[90] R. Wright, G. Saphiz, W. M. Powell, G. Maenchen, W. B. Fowler, Phys. Rev. **100**, 1802 (1955).

[91] R. Kalbach, I. Lord, T. Tsao, Phys. Rev. **113**, 325, 330 (1959).

[92] N. P. Bogachev, S. A. Bunjatov, I. M. Gramenitski et al., Žurn. ėksper. teor. Fiz. **37**, 1225 (1959); JETP **10**, 872 (1960).

[93] A. Ashmore, G. Cocconi, A. N. Diddens, A. M. Wethirell, Phys. Rev. Lett. **5**, 576 (1960).

[94] V. A. Nikitin, V. A. Sviridov, K. D. Tolstov, Preprint of JINR P-677, 1961.

[95] I. Marshall, L. Marshall, V. A. Nedzel, Phys. Rev. **98**, 1513 (1955).

[96] S. K. Kao, H. Hortman, G. W. Hinman, Phys. Rev. **119**, 381 (1960).

[*97*] R. B. Sutton, T. H. Fields, I. G. Fox, I. A. Kane, W. E. Mott, R. A. Stallwood. Phys. Rev. **97**, 783 (1955).

[*98*] L. O. Roellig, D. A. Glaser, Phys. Rev. **116**, 1001 (1959).

[*99*] A. P. Batson, B. B. Culwick, L. Riddiford, Walker, CERN-Symposium (Geneva) **2**, 340 (1956).

[*100*] I. D. Dowell, W. R. Frisken, G. Martelli, B. Musgrave, Prog. Phys. Soc. **74**, 625 (1959).

[*101*] A. P. Batson, B. B. Culwick, I. G. Hill, L. Riddiford, Proc. Roy. **251**, 218 (1959).

[*102*] A. P. Batson, B. B. Culwick, I. G. Hill, L. Riddiford, Proc. Roy. Soc. **251**, 233 (1959).

[*103*] I. D. Dowell, W. R. Frisken et al., Nuovo Cimento **18**, 818 (1960).

[*104*] I. D. Dowell, W. R. Frisken et al., Proc. of the 10-th International Conference on High Energy Phys., Rochester, 1960.

[*105*] W. B. Fowler, R. P. Shutt, A. M. Thorndike, W. L. Whittermore, Phys. Rev. **103**, 1479 (1956).

[*106*] R. C. Whitten, M. M. Block, Phys. Rev. **111**, 1676 (1958).

[*107*] M. M. Block, E. M. Harth, V. T. Cocconi et al., Phys. Rev. **103**, 1484 (1956).

[*108*] S. A. Azimov, G. G. Arushanov, A. A. Juldashev, Dokl. Uz. Akad. Nauk (in print).

[*109*] G. Smith, H. Courant, E. Fowler, H. Kraybill, S. Sandwiss, H. Taft, Proc. of the 10-th Intern. Conference on High Energy Phys., Rochester, 1960.

[*110*] R. E. Cavananch, B. M. Haskin, M. Schein, Phys. Rev. **100**, 1263 (1955).
M. Schein, D. M. Haskin, R. G. Glasser, Nuovo Cimento **3**, 131 (1956).

[*111*] G. Wentzel, CERN, Symposium, 1958.

[*112*] P. K. Marjov, E. N. Tzuganov, M. I. Shafranova, B. A. Shakhbazjan, Žurn. èksper. teor. Fiz. **38**, 1471 (1960); JETP **11**, 1063 (1960).

[*113*] A. F. Dunajtsev, Ju. D. Prokoshkin, Žurn. èksper. teor. Fiz. **36**, 1656 (1959); JETP **9**, 1159 (1959).

[*114*] A. H. Rosenfeld, Phys. Rev. **96**, 139 (1954).

[*115*] F. S. Crawford, I. Stevenson, Phys. Rev. **91**, 468 (1953).

[*116*] R. Durbin, H. Loar, I. Steinberger, Phys. Rev. **84**, 581 (1951).

[*117*] T. H. Fields, I. G. Fox, I. A. Kane, R. A. Stallwood, R. B. Sutton, Phys. Rev. **109**, 1704, 1713, 1716 (1958).

[*118*] B. S. Neganov, O. V. Savchenko, Žurn. èksper. teor. Fiz. **32**, 1265 (1957); JETP **5**, 1033 (1957).

[*119*] H. L. Stadler, Phys. Rev. **96**, 496 (1954).

[*120*] M. G. Meshchryakov, B. S. Neganov, Dokl. Akad. Nauk SSSR **100**, 677 (1955).

[*121*] T. H. Fields, I. G. Fox, I. A. Kane, R. A. Stallwood, R. B. Suttan, Phys. Rev. **95**, 638 (1954).

[*122*] H. Winzeler, B. Klaiber, W. Koch, M. Nicolić, M. Schneeberger, Nuovo Cimento **17**, 8 (1960).

[*123*] E. Melkonian. Phys. Rev. **76**, 1744, 1750 (1949).

[*124*] R. E. Fields, R. L. Becker, R. K. Adair, Phys. Rev. **94**, 389 (1954).

[*125*] C. L. Storrs, D. H. Frisch, Phys. Rev. **95**, 1252 (1954).

[*126*] E. M. Hafner, W. F. Hornyak, G. E. Falk, G. Snow, T. Coor, Phys. Rev. **89**, 204 (1953).

[*127*] A. Bratenahl, I. M. Peterson, I. P. Stoering, Phys. Rev. **110**, 927 (1958).

[*128*] W. Sleator, Phys. Rev. **72**, 207 (1947).

[*129*] M. Ageno, E. Amaldi, D. Bocciarelli, G. C. Trabachi, Phys. Rev. **71**, 20 (1947).

[*130*] A. H. Lasday, Phys. Rev. **81**, 139 (1951).

[*131*] E. O. Solant, N. F. Ramsey, Phys. Rev. **57**, 1075 (1940).

[*132*] L. S. Goodman, Phys. Rev. **88**, 686 (1952).

[*133*] H. L. Poss, E. O. Salant, G. A. Snow, Luke C. L. Yuan, Phys. Rev. **87**, 11 (1952).

[*134*] I. H. Coon, E. R. Graves, H. H. Barschall, Phys. Rev. **88**, 562 (1952).

[*135*] R. B. Day, R. L. Mills, I. E. Perry, Jr. and F. Scherb, Phys. Rev. **114**, 209 (1959); **98**, 279 (1955).

[*136*] R. B. Day, R. L. Henkel, Phys. Rev. **92**, 358 (1953).
[*137*] R. Sherr, Phys. Rev. **68**, 240 (1945).
[*138*] I. E. Brolley, I. H. Coon, I. L. Fowler, Phys. Rev. **82**, 190 (1951).
[*139*] A. E. Taylor, E. Wood, Phil. Mag. **44**, 95 (1953); 42, 751 (1951).
[*140*] E. A. Taylor, T. G. Pickavance, I. M. Cassels, T. C. Randle, Phil. Mag. **42**, 328 (1951).
[*141*] R. H. Hildebrand, C. Leith, Phys. Rev. **80**, 842 (1950).
[*142*] I. Hadley, K. Kelly, C. Leith, E. Segré, C. Wiegand, H. York, Phys. Rev. **75**, 351 (1949).
[*143*] P. Hillman, R. H. Stahl, N. F. Ramsey, Phys. Rev. **96**, 115 (1954).
[*144*] L. I. Cook, E. M. McMillan, I. M. Peterson, D. S. Sewell, Phys. Rev. **75**, 7 (1949).
[*145*] Chung Ying Chih, W. M. Powell, Phys. Rev. **106**, 539 (1957).
[*146*] V. Culler, R. W. Waniek, Phys. Rev. **99**, 740 (1955).
[*147*] I. De Juren, N. Knable, Phys. Rev. **77**, 606 (1950).
[*148*] G. R. Mott, G. L. Guernsey, B. K. Nelson, Phys. Rev. **88**, 9 (1952).
[*149*] I. De Juren, B. I. Moyer, Phys. Rev. **81**, 919 (1951).
[*150*] A. E. Taylor, Phys. Rev. **92**, 1071 (1953).
[*151*] H. G. de Carvalho, Phys. Rev. **96**, 398 (1954).
[*152*] E. Kelly, C. Leith, E. Segré, C. Wiegand, Phys. Rev. **79**, 96 (1950).
[*153*] I. de Juren, Phys. Rev. **80**, 27 (1950).
[*154*] R. Fox, G. Leith, L. Wouters, K. R. MacKenzie, Phys. Rev. **80**, 23 (1950).
[*155*] A. Ashmore, R. G. Jarvis, D. S. Mather, S. K. Sen, Proc. Phys. Soc. **70**, 745 (1957).
[*156*] V. P. Dzhelepov, Ju. M. Kazarinov, B. M. Golovin, V. B. Flyagin, V. I. Satarov, Izv. Akad. Nauk SSSR **19**, 573 (1955); Dokl. Akad. Nauk **104**, 717 (1955); V. P. Dzhelepov, Ju. M. Kazarinov, Dokl. Akad. Nauk **99**, 939 (1954).
[*157*] F. F. Chen, C. P. Leavitt, A. M. Shapiro, Phys. Rev. **103**, 211 (1956); **95**, 663 (1954).
[*158*] I. Marshall, L. Marshall, V. A. Nedzel, Phys. Rev. **91**, 767 (1953).
[*159*] V. A. Nedzel, Phys. Rev. **94**, 174 (1954).
[*160*] N. E. Booth, G. W. Hutchinson, B. Ledley, Proc. Phys. Soc. **71**, 293 (1958).
[*161*] V. Perez-Mendez, I. M. Atkinson, W. N. Hess, R. W. Wallace, Bull. Amer. Phys. Soc. **4**, 253 (1959).
[*162*] I. de Pangher, Phys. Rev. **99**, 1447 (1955).
[*163*] G. B. Yodh, Phys. Rev. **98**, 1330 (1955)
[*164*] A. F. Dunajtsev, Ju. D. Prokoshkin, Žurn. ėksper. teor. Fiz. **38**, 747 (1960); JETP **11**, 540 (1960).
[*165*] A. F. Dunajtsev, Ju. D. Prokoshkin, Žurn. ėksper. teor. Fiz. **36**, 1656 (1959); JETP **9**, 1179 (1959); B. S. Neganov, O. V. Savchenko, Žurn. ėksper. teor. Fiz. **32**, 1265 (1957); JETP **5**, 1033 (1957).
[*166*] V. P. Dzhelepov, V. S. Kiselev, K. O. Oganesyan, V. B. Flyagin, Meterials of the X-th International Conference on High Energy Physics, Rochester, 1960.
[*167*] E. M. Baldwin, Phys. Rev. **83**, 495 (1951).
[*168*] I. H. Atkinson, W. N. Hess, V. Perez-Mendez, R. W. Fallace, Phys. Rev. Lett. **2**, 168 (1959).
[*169*] W. Y. Pajopadhue, Phil. Mag. **5**, 537 (1960).
[*170*] M. V. K. Appa Rao, R. R. Daniel, K. A. Neelakantan, Proc. Ind. Acad. of Sc. **18**, 181 (1956).
[*171*] R. Daniel, N. Kamesware Rao, P. Mathotza, Y. Tsuzuki, Materials of the 9-th International Conference on High Energy Physics, Kiew, 1959.
[*172*] G. Williams, Master's Thesis. University of Washington, 1958 (cited by [*171*]).
[*173*] Wang Shu-Fen, T. Vishki, I. M. Gramenitsi et al., Preprint of JINR, P-526, 1960.
M. I. Podgoretsky (private communication).
[*174*] K. I. Alekseev, N. A. Grigorov, Dokl. Akad. Nauk **117**, 593 (1957).
[*175*] R. B. Begzhanov, Žurn. ėksper. teor. Fiz. **34**, 775 (1958); JETP **7**, 534 (1958).
[*176*] L. E. Brenner, R. W. Williams, Phys. Rev. **106**, 1020 (1957).

[*177*] M. W. Teucher, E. Lohrmann, Bull. Amer. Phys. Soc. **5**, 24 (1960).
[*178*] N. Horwitz, D. Miller, I. Murray, R. Tripp, Phys. Rev. **115**, 472 (1959).
[*179*] L. E. Agnew, I. T. Elioff et al., Phys. Rev. **118**, 1371 (1960).
[*180*] L. Agnew, T. Alioff et al., Phys. Rev. **110**, 994 (1958).
[*181*] C. A. Coombes, B. Sork, W. Galbraith, G. R. Lambertson, W. A. Wenzel, Phys. Rev. **112**, 1303 (1958).
[*182*] A. Engler, P. B. Jones, I. H. Mulvey, Proc. Roy. Soc. **254** A, 425 (1960).
[*183*] A. G. Ekspong, B. E. Ronne, Nuovo Cimento **13**, 27 (1959).
[*184*] G. Baroni, G. Bellettini et al., Nuovo Cimento **12**, 564 (1959).
[*185*] G. Goldhaber, K. Kalageroupoulos, R. Silber, Phys. Rev. **110**, 1474 (1958).
[*186*] E. Amaldi, G. Baroni et al., Nuovo Cimento **14**, 977 (1959).
[*187*] B. Cork, G. R. Lambertson, O. Piccioni, W. Wenzel, Phys. Rev. **107**, 248 (1957).
[*188*] I. Button, T. Elioff, E. Segré et al., Phys. Rev. **108**, 1557 (1957).
[*189*] O. Chamberlain, D. V. Keller, R. Mermod et al., Phys. Rev. **108**, 1553 (1957).
[*190*] T. Elioff, O. Chamberlain, H. M. Steiner, C. Wiegand, T. Ypsilantis, Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.
[*191*] T. Elioff, L. Agnew et al., Phys. Rev. Lett. **3**, 285 (1959).
[*192*] R. Armenteros, C. A. Coombes, B. Cork, G. A. Lambertson, W. A. Wenzel, Phys. Rev. **119**, 2068 (1960).
[*193*] T. Elioff, Proc. of the 10-th International Conference on High Energy Phys., Rochester, 1960.
[*194*] R. Armenteros, C. A. Coombes, B. Cork, G. A. Lambertson, W. A. Wenzel, UCRL – 8851 (1960).
[*195*] I. C. Brisson, I. F. Dotoeuf, P. Falk-Vairant, L. van Rossum, G. Valladas, L. C. L. Yuan, Phys. Rev. Lett. **3**, 561 (1959).
I. C. Brisson, I. F. Detoeuf, P. Falk-Vairant, L. van Rossum, G. Valladas, Preprint Saclay, 1960. The data of the previous publication have been specified and corrected in this preprint.
[*196*] H. C. Burrowes, D. O. Caldwell et al., Phys. Rev. Lett. **2**, 119 (1959).
[*197*] M. C. Rinehart, R. C. Rogers, L. M. Lederman, Phys. Rev. **100**, 883 (1955).
[*198*] D. E. Nagle, D. H. Hildebrand, R. I. Plano, Phys. Rev. **105**, 718 (1957).
[*199*] W. Spry, Phys. Rev. **95**, 1295 (1954).
[*200*] I. Orear, W. Slater, I. I. Lord, S. L. Eilenberger, A. B. Weaver, Phys. Rev. **96**, 174 (1954).
[*201*] A. Roberts, I. Tinlot, Phys. Rev. **90**, 951 (1953).
[*202*] C. E. Angell, I. P. Perry, Phys. Rev. **92**, 835 (1953).
[*203*] I. Tinlot, A. Roberts, Phys. Rev. **95**, 137 (1954).
[*204*] S. Barnes, R. Rose, G. Giacomelli et al., Nuovo Cimento **10**, 734 (1958).
[*205*] P. Isaacs, A. Sachs, I. Steinberger, Phys. Rev. **85**, 803 (1953).
[*206*] D. Bodansky, A. Sachs, I. Steinberger, Phys. Rev. **93**, 1367 (1954).
[*207*] C. M. York, W. I. Kernan, E. L. Garwin, Phys. Rev. **119**, 1096 (1960).
[*208*] H. L. Anderson, E. Fermi, D. A. Nagle, G. B. Yodh, Phys. Rev. **86**, 413 (1952).
[*209*] G. Goldhaber, Phys. Rev. **89**, 1187 (1953).
[*210*] C. Chedester, P. Isaacs, A. Sachs, I. Steinberger, Phys. Rev. **82**, 958 (1951).
[*211*] H. L. Anderson, E. Fermi, D. A. Nagle, G. B. Yodh, Phys. Rev. **86**, 793 (1952).
[*212*] H. L. Anderson, E. Fermi, E. A. Long, R. Martin, D. E. Nagle, Phys. Rev. **85**, 934 (1952).
[*213*] D. N. Edwards, G. S. F. Frank, I. R. Holt, Proc. Phys. Soc. **73**, 856 (1959).
[*214*] I. Orear, Phys. Rev. **92**, 156 (1953).
[*215*] H. L. Anderson, E. Fermi, R. Martin, D. E. Nagle, Phys. Rev. **91**, 155 (1953).
[*216*] Ju. A. Budagov, S. Vivtor, V. P. Dzhelepov, P. F. Yermolov, V. I. Moskalev, Žurn. ėksper. teor. Fiz. **38**, 734 (1960); JETP **11**, 531 (1960).
[*217*] E. L. Garwin, W. I. Kernan, C. O. Kim, C. M. York, Phys. Rev. **115**, 1295 (1959).
[*218*] V. E. Kruse, R. C. Arnold, Phys. Rev. **116**, 1008 (1959).

[219] V. E. Kruse, R. C. Arnold, Proc. of the 9-th Intern. Conf. on High Energy Phys., Kiew, 1959.

[220] A. E. Ignatenko, A. I. Mukhin, E. B. Ozerov, B. M. Pontecorvo, Dokl. Akad. Nauk **103**, 45 (1955).

[221] I. Ashkin, I. P. Blaser, F. Feiner, M. O. Stern, Phys. Rev. **101**, 1149 (1956).

[222] W. I. Kernan, Phys. Rev. **119**, 1092 (1960).

[223] I. Ashkin, I. P. Blaser, F. Feiner, I. G. Gorman, M. O. Stern, Phys. Rev. **96**, 1104 (1954).

[224] V. I. Zinov, A. D. Konin, S. M. Korenchenko, B. M. Pontecorvo, Preprint of JINR—455 (1959).

[225] H. L. Anderson, M. Glicksman, Phys. Rev. **100**, 268 (1955).

[226] E. Fermi, M. Glacksman, R. Martin, D. Nagle, Phys. Rev. **92**, 161 (1953).

[227] M. Glicksman, Phys. Rev. **95**, 1045 (1954).

[228] M. Glicksman, Phys. Rev. **94**, 1335 (1954).

[229] I. Ashkin, I. P. Blaser, F. Feiner, M. O. Stern, Phys. Rev. **105**, 724 (1957).

[230] I. Deahl, M. Derrick, I. Fetkovich, T. Fields, G. B. Yodh, Proc. of the 10-th Intern. Conference of High Energy Phys., Rochester, 1960.

[231] V. G. Zinov, S. M. Korenchenko, Žurn. èksper. teor. Fiz. **36**, 618 (1959); JETP **9**, 429 (1959).

[232] V. G. Zinov, S. M. Korenchenko, Žurn. èksper. teor. Fiz. **38**, 1399 (1960); JETP **11**, 1010 (1960).

[233] V. G. Zinov, S. M. Korenchenko, Žurn. èksper. teor. Fiz. **38**, 1099 (1960); JETP **11**, 794 (1960)

[234] W. Perkins, I. Caris, R. Kenney, V. Perez-Mendez, Phys. Rev. Lett. **4**, 391 (1960).

[235] L. C. Yuan, S. L. Linderbaum, Phys. Rev. **100**, 306 (1955).

[236] M. M. Vasilevski, V. V. Vishnjakov, Žurn. èksper. teor. Fiz. **38**, 441 (1960); JETP **11**, 323 (1960).

[237] L. S. Dulkova, J. B. Sokolova, M. I. Shafranova, Dokl. Akad. Nauk **111**, 992 (1956).

[238] V. V. Petrilka, Materials of the 10-th International Conference on High Energy Physics, Rochester, 1960.

[239] V. I. Zinov, S. M. Korenchenko, Žurn. èksper. teor. Fiz. **33**, 1308 (1957); JETP **6**, 1007 (1958).

[240] V. I. Zinov, S. M. Korenchenko, Žurn. èksper. teor. Fiz. **34**, 301 (1958); JETP **7**, 210 (1958).

[241] M. Kozodajew, R. Suljaev, A. Filipov, Ju. Scherbakov, Dokl. Akad. Nauk **107**, 236 (1956).

[242] V. I. Zinov, S. M. Korenchenko, Žurn. èksper. teor. Fiz. **33**, 1307 (1957); JETP **6**, 1006 (1958).

[243] L. K. Goodwin, R. W. Kenney, V. Perez-Mendez, Phys. Rev. Lett. **3**, 522 (1959).

[244] T. I. Devlin, B. C. Barish, W. W. Hess, V. Perez-Mendez, I. Solomon, Phys. Rev. Lett. **4**, 242 (1960).

[245] R. Cool, L. Madansky, O. Piccioni, Phys. Rev. **93**, 637 (1954).

[246] R. Cool, O. Piccioni, D. Clark, Phys. Rev. **103**, 1082 (1956).

[247] R. R. Crittenden, I. H. Scandrett, W. D. Shephard, W. D. Walker, I. Ballam, Phys. Rev. Lett. **2**, 121 (1959).

[248] A. M. Shapiro, C. P. Leavitt, F. F. Chen, Phys. Rev. **92**, 1072 (1953).

[249] J. I. Shonle, Phys. Rev. Lett. **5**, 156 (1960).

[250] L. Goodwin, J. Caris, Proc. of the 10-th Intern. Conference on High Energy Phys., Rochester, 1960. UCRL-9119 (1960).

[251] Ju. Batusov, S. Bunjatov, V. Sidorov, V. Jarba, Materials of the X-th Intern. Conference on High Energy Physics, Rochester, 1960.

[252] Ju. Batusov, N. Bogachev, S. Bunjatov, V. Sidorov, V. Jarba, Dokl. Akad. Nauk **133**, 52 (1960).

[253] B. McCormica, L. Baggett, CERN, Symposium, 1958.

[254] W. D. Walker, F. Hushfar, W. D. Shephard, Phys. Rev. **104**, 526 (1956).

[255] S. Bergia, L. Bertocchi et al., Nuovo Cimento **15**, 551 (1960).

[256] A. R. Erwin, J. K. Kopp, Phys. Rev. **109**, 1364 (1958).

[257] V. Alles-Borelli, S. Bergia, E. Perez-Mendez, P. Waloschek, Nuovo Cimento **14**, 211 (1959).

[258] I. Derado, G. Lütjens, N. Schmitz, Ann. Phys. Leipzig **4**, 103 (1959).

[259] I. Derado, N. Schmitz, Phys. Rev. **118**, 309 (1960).

[260] M. Chretien, I. Leither, N. Samies, M. Schwarty, I. Steinberger, Phys. Rev. **108**, 383 (1957); CERN, Symposium, 1958.

[261] L. M. Eiaberg, W. G. Fowler et al., Phys. Rev. **97**, 797 (1955).

[262] R. P. Shutt et al., CERN, Symposium.

[263] W. D. Walker, Phys. Rev. **108**, 782 (1958).

[264] N. F. Wikner, UCRL-3659 (1957); cited by [*263*].

[265] K. C. Bandtel, H. A. Bostick, B. J. Moyer, R. W. Wallace, N. F. Wikner, Phys. Rev. **99**, 673 (1955).

[266] W. B. Fowler, Proc. of the 6-th Intern. Conf. on High Energy Phys., Rochester. 1956.

[267] G. Maenchen et al., CERN, Symposium, 1958.

[268] G. Maenchen, W. B. Fowler, W. M. Powell, R. W. Wrigth, Phys. Rev. **108**, 850 (1957).

[269] R. G. Thomas, Jr., Phys. Rev. Lett. **5**, 229 (1960); Phys. Rev. **120**, 1021 (1960).

[270] R. G. Thomas, UCRL—8965 (1959), see [*89*].

[271] Wang Kan-Chang, Wang Tzu-Tzen, Ding Da-Tsao, V. I. Ivanov et al., Preprint of JINR, P-393 (1959).

[272] Wang Kan-Chang, Wand Tsu-Tsen et al., private communication of Ju. Kladnitskaja.

[273] D. Radojicic, Private communication (cited by the paper P. F. Priorls, Phys. Rev. Lett. **5**, 166 (1960)).

[274] J. J. Shalamov, V. A. Shebanov, Žurn. èksper. teor. Fiz. **39**, 1232 (1960); JETP **12**. 859 (1961).

[275] J. Bartke, R. Bock, W. A. Cooper et al., Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.

[276] G. E. Fischer, E. M. Jenkins, Phys. Rev. **116**, 749 (1959).

[277] W. H. Evans, CERN, Symposium (1956).

[278] J. Orear, Bull. Phys. Soc. **29** (No. 7) 24 (1954).

[279] S. L. Whetstone, D. H. Stork, Phys. Rev. **102**, 251 (1956).

[280] D. Miller, J. Ring, Phys. Rev. **117**, 582 (1960).

[281] W. B. Johnson, M. Camac, Bull. Amer. Phys. Soc. **3**, 197 (1958).

[282] S. Leonard, D. H. Stoork, Phys. Rev. **93**, 568 (1954).

[283] J. P. Perry, C. E. Angell, Phys. Rev. **91**, 1289 (1953).

[284] S. W. Barnes, B. Rose et al., Phys. Rev. **117**, 226 (1960).

[285] J. Orear, J. J. Lord, A. B. Weaver, Phys. Rev. **93**, 575 (1954).

[286] H. L. Anderson, E. Fermi, E. A. Long, D. Nagle, Phys. Rev. **85**, 936 (1952).

[287] L. Ferretti, G. Guareni, M. Della Corte, T. Fazzini, Nuovo Cimento **5**, 1660 (1957).

[288] G. Ferrari, L. Ferretti et al., CERN, Symposium **2**, 230 (1956).

[289] R. Gessaroli, G. Quareni, Nuovo Cimento **5**, 1658 (1957).

[290] J. Orear, Phys. Rev. **96**, 1417 (1954).

[291] A. Loria, P. Mittner, R. Santengelo, G. Zago, A. Brenner, J. L. Montanet, Proc. of the 9-th Intern. Conf. on High Energy Phys., Kiev, 1959.

[292] A. E. Ignatenko, A. I. Mukhin, E. B. Ozerov, B. M. Pontecorvo, Žurn. èksper. teor. Fiz. **30**, 7 (1956); JETP **3**, 10 (1956).

[293] J. Orear, C. H. Tsao, J. J. Lord, A. B. Weaver, Phys. Rev. **95**, 624 (1954).

[294] S. J. Lindenbaim, L. C. L. Yuan, Phys. Rev. **111**, 1380 (1958).

[*295*] S. J. Lindenbaum, L. C. L. Yuan, Proc. Roch. Fourth Conf. on High Nucl. Phys., 99 (1954) Rochester.

[*296*] R. A. Grandey, A. F. Clark, Phys. Rev. **97**, 791 (1955).

[*297*] G. Homa, G. Goldhaber, L. M. Ledermann, Phys. Rev. **93**, 554 (1954).

[*298*] A. I. Mukhin, E. B. Ozerov, B. M. Pontecorvo, Žurn. èksper. teor. Fiz. **31**, 371 (1956); JETP **4**, 237 (1957).

[*299*] H. L. Anderson, W. G. Davidon, M. Glicksman, V. E. Kruse, Phys. Rev. **100**, 279 (1955).

[*300*] W. B. Fowler, R. M. Lea et al., Phys. Rev. **92**, 832 (1953).

[*301*] L. O. Roellig, Doctor dissertation, University of Michigan, 1959.

[*302*] I. D. Crew, R. D. Hill, Phys. Rev. **110**, 177 (1958); W. D. Walker, I. Crussard, Phys. Rev. **98**, 1416 (1955).

[*303*] I. Likhachev, V. Stavinsky, Sui Yuin-chan, Materials of the 9-th International Conference on High Energy Physics, Kiev, 1959.

[*304*] T. J. Devlin, B. C. Barish, W. N. Hess, V. Perez-Mendez, J. Solomon, Phys. Rev. Lett. **4**, 242 (1960).

[*305*] W. J. Willis, Phys. Rev. **116**, 753 (1959).

[*306*] G. Ferrari, E. Manaresi, G. Quareni, Nuovo Cimento **5**, 1651 (1957).

[*307*] A. M. Sachs, H. Winick, B. A. Wooten, Phys. Rev. **109**, 1750 (1958).

[*308*] A. M. Sachs, H. Winick, B. A. Wooten, Phys. Rev. **100**, 1255 (1955).

[*309*] E. C. Fowler, W. B. Fowler et al., Phys. Rev. **86**, 1053 (1952).

[*310*] H. D. Taft, Phys. Rev. **101**, 1116 (1956).

[*311*] M. F. Likhachev, K. S. Stavinsky, Sui Yuin-chan, Chzan Nai-sen, Preprint of JINR P-659 (1961).

[*312*] Preliminary result obtained at CERN, Adams, Report at Dubna, june, 1960.

[*313*] M. Derrick, I. Fetkovich, T. Fields, E. G. Pewitt, G. B. Yodh, Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.

[*314*] R. E. Cavananch, D. M. Haskin, M. Schein, Phys. Rev. **100**, 1263 (1955); M. Schein, D. M. Haskin, R. G. Glasser, Nuovo Cimento **3**, 131 (1956).

[*315*] I. O. Slarke, S. V. Maior, Phil. Mag. **2**, 37 (1957).

[*316*] A. Marques, N. Margem, G. A. B. Garnier, Nuovo Cimento **5**, 291 (1957).

[*317*] D. I. Holthuizer, B. Iongejans, Nuovo Cimento **14**, Suppl. 2, 429 (1959).

[*318*] V. A. Belyakov, Wang Shu-fen, V. V. Glagolev, N. Dalkhazhav et al., Preprint of JINR P-530 (1960).

[*319*] K. Lanius, Report at the Emulsion Meeting, Dubna, 1960.

[*320*] A. Debenedetti, C. M. Garelli, L. Tallone, M. Vigone, Nuovo Cimento **4**, 1442 (1956).

[*321*] Lee Baggett, UCRL-8302 (1958); cited by [*249*].

[*322*] W. D. Walker, J. Crussard, Phys. Rev. **98**, 1416 (1955).

[*323*] Materials of the 10-th International Conference on High Energy Physics, Rochester, 1960.

[*324*] A. L. Lubimov et al., Materials of the 10-th International Conference on High Energy Physics, Rochester, 1960.

[*325*] M. Alston, L. W. Alvarez, P. Eberhart, M. I. Good et al., Phys. Rev. Lett. **5**, 520 (1960).

[*326*] M. Ferro-Luzzi, J. P. Berge et al., Bull. Amer. Phys. Soc. **5**, 509 (1960).

[*327*] S. Minami, "Exited state in $\Lambda\pi$-system and K^-p-Collisions" preprint (1960).

[*328*] J. u. A. Batusov, S. A. Bunjatov, V. M. Sidorov, V. A. Jarba, Žurn. èksper. teor. Fiz. **39**, 506 (1960); JETP **12**, 354 (1961).

[*329*] F. Dyson, Phys. Rev. **99**, 1026 (1955); G. Takeda, Phys. Rev. **100**, 440 (1955).

[*330*] V. I. Ruskin, Žurn. èksper. teor. Fiz. **36**, 164 (1959); JETP **9**, 113 (1959); V. S. Barashenko, V. M. Maltsev, Žurn. èksper. teor. Fiz. **37**, 884 (1959); JETP **10**, 630 (1960); R. Hagedorn, Nuovo Cimento **15**, 246 (1960); V. I. Ruskin, P. A. Usik, Žurn. èksper. teor. Fiz. **38**, 929 (1960); JEPT **11**, 669 (1960.

[331] E. Eberle, Nuovo Cimento **8**, 610 (1958); T. Goto, Nuovo Cimento **8**, 625 (1958); F. Cerulus, Nuovo Cimento **14**, 827 (1959); V. M. Maximenko, Žurn. ksper. teor. Fiz. **38**, 652 (1960); JETP **11**, 469 (1960); V. S. Barashenkov, Fortschr. Phys. **9**, 42 (1961).

[332] W. R. Frazer, J. R. Fulco, Phys. Rev. **117**, 1609 (1960).

[333] Chou Kuang-chao, Ho Tso-hsiu, Žurn. èksper. teor. Fiz. **39**, 1485 (1960); JETP **12**, 1032 (1961).

[334] A. Abashian, N. E. Booth, K. M. Crowe, Proc. of the 10-th International Conf. on High Energy Phys., Rochester, 1960.

[335] W. Alles, N. N. Biswas et al., Nuovo Cimento **11**, 771 (1959).

[336] P. Nordin, A. Rosenfeld, F. Solmitz, R. Tripp, M. Watson, Bull. Amer. Phys. Soc. **4**, 24 (1959).

[337] P. Nordin, A. H. Rosenfeld, F. T. Solmitz, R. D. Tripp, M. B. Watson, Bull. Amer. Phys. Soc. **4**, 228 (1959).

[338] H. C. Burrowes, D. O. Caldwell et al., Phys. Rev. Lett. **2**, 117 (1959).

[339] P. Eberhard, A. H. Rosenfeld, F. T. Solmitz, R. D. Tripp, M. B. Watson, Phys. Rev. **2**, 312 (1959).

[340] B. Cork, G. R. Lambertson, O. Piccioni, W. Wenzel, Phys. Rev. **106**, 167 (1957).

[341] S. C. Freden, F. C. Gilbert, R. S. White, Phys. Rev. **118**, 564 (1960); Phys. Rev. Lett. **4**, 265 (1960).

[342] F. C. Gilbert, C. E. Violet, R. C. White, Phys. Rev. **103**, 1825 (1956).

[343] L. W. Alvarez, H. Bradner et al., Nuovo Cimento **5**, 1026 (1957).

[344] R. G. Glasser, N. Seeman, G. A. Snow, Nuovo Cimento **7**, 142 (1958).

[345] R. S. White, S. C. Freden, F. C. Gilbert, Bull. Amer. Phys. Soc. **4**, 24 (1959).

[346] R. G. Glasser, N. Seeman, G. A. Snow, Nuovo Cimento **9**, 1085 (1958).

[347] W. Alles, N. N. Biswas, M. Ceccarelli, I. Crussard, Nuovo Cimento **6**, 571 (1957).

[348] E. Lohgman, M. Nikolić et al., Nuovo Cimento **7**, 163 (1958).

[349] F. N. Webb, E. L. Iloff et al., Nuovo Cimento **8**, 899 (1958).

[350] G. Ascoli, R. D. Hill, T. S. Yoon, Nuovo Cimento **9**, 813 (1958).

[351] D. Evans, F. Hassan, K. K. Nagpaul et al., Nuovo Cimento **15**, 873 (1960).

[352] H. Göing, Nuovo Cimento **16**, 848 (1960).

[353] S. Nilsson, A. Frisk, Ark. Fys. **14**, 277 (1958).

[354] P. Nordin, Bull. Amer. Phys. Soc. **3**, 336 (1958).

[355] A. H. Rosenfeld, Bull. Amer. Phys. Soc. **3**, 363 (1958).

[356] B. Cork, G. R. Lambertson, O. Piccioni, W. Wenzel, Alvarez's report — Proc. of the 9-th Intern. Conf. on High Energy Phys., Kiev, 1959.

[357] L. Alvarez, P. Eberhard et al., Proc. of the 9-th Intern. Conf. on High Energy Phys., Kiev, 1959.

[358] V. Cook, B. Cork, T. F. Hoang, D. Keefe et al., UCRI-9386 (1961).

[359] G. van Dardel, D. H. Frisch, R. Mermod, R. H. Milburn et al., Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.

[360] Alvarez's report; Materials of the 9-th International Conference on High Energy Physics, Kiev, 1959.

[361] P. Bastien, O. Dahl et al., Bull. Amer. Phys. Soc. **5**, 509 (1960).

[362] T. F. Kycia, L. T. Kerth, R. G. Baender, Bull. Amer. Phys. Soc. **4**, 25 (1959).

[363] D. T. Meyer, M. L. Perl, D. A. Glaser, Phys. Rev. **107**, 279 (1957).

[364] D. F. Hoang, M. F. Kaplon, R. Cester, Phys. Rev. **107**, 1698 (1957).

[365] Ann. International Conference CERN, sess. **6**, 172 (1958).

[366] E. Helmi, O. R. Price, D. Prouse, D. Stork, H. K. Ticho, Alvarez's report — Proc. of the 9-th Conf. on High Energy Phys., Kiev, 1959.

[367] D. Stork, D. Prowse (cited by [368]).

[368] T. F. Kycia, L. T. Kerth, R. G. Baender, Phys. Rev. **118**, 553 (1960).

[369] I. E. Lannutti, W. Chupp et al., Phys. Rev. **101**, 1617 (1956).

[370] N. N. Biswas, L. Cecarelli-Fabbrichesi et al., Nuovo Cimento **5**, 123 (1957).

[371] G. Cocconi, G. Puppi, G. Quareni, A. Stangellini, Nuovo Cimento **5**, 172 (1957).

[*372*] M. Baldo Ceolin, M. Cresti et al., Nuovo Cimento **5**, 402 (1957).

[*373*] M. Grilli, L. Guerriero, M. Merlin, Z. O'Friel, G. A. Salandin, Nuovo Cimento **9**, 358 (1958).

[*374*] D. Keefe, A. Kerman, A. Montwill, Nuovo Cimento **10**, 538 (1958).

[*375*] B. Showmik, D. Evans et al., Nuovo Cimento **6**, 440 (1957).

[*376*] N. N. Biswas, L. Ceccarelli-Fabbrichesi et al., Nuovo Cimento **3**, 1481 (1956).

[*377*] D. Keefe, A. Kerman et al., Nuovo Cimento **12**, 241 (1959).

[*378*] M. Grilli, L. Guerriero, M. Merlin, A. O'Friel, G. Salandin, Nuovo Cimento **10**, 163 (1958).

[*379*] D. Evans, F. Hassan et al., Nuovo Cimento **10**, 168 (1958).

[*380*] M. Grilli, L. Guerriero, M. Merlin, G. Salandin, Nuovo Cimento **10**, 205 (1958).

[*381*] I. E. Lannutti, S. Goldhaber et al., Rep. Padua-Venice Conf. sess. **3**, 1 (1957); Phys. Rev. **109**, 2121 (1958).

[*382*] L. T. Kerth, T. F. Kycia, L. van Rossum, Rep. Padua-Venice Conf. sess. **3**, 28 (1957).

[*383*] B. Sechi-Zorn, G. T. Zorn, Phys. Rev. **108**, 1098 (1957).

[*384*] M. Grilli, L. Guerriero, G. A. Salandin, Padua-Venice Conf. sess. **3**, 16 (1957).

[*385*] W. Chinowsky, G. Goldhaber, S. Goldhaber et al, Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.

[*386*] C. Ceolin, N. Dallaporta et al., Nuovo Cimento **13**, 818 (1959).

[*387*] M. Widgoff, A. Pevsner et al., Phys. Rev. **107**, 1430 (1957).

[*388*] D. Davis, N. Kwak, M. Kaplon, Phys. Rev. **117**, 846 (1960).

[*389*] B. Sechi-Zorn, G. T. Zorn, Phys. Rev. **120**, 1898 (1960).

[*390*] Wang Kan-chang, A. K. Mihul et al., (will be published).

[*391*] Wang Kan-chang, V. I. Veksler et al., Preprint of JINR D-594 (1960).

[*392*] V. S. Barashenkov, Nucl. Phys. **15**, 486 (1960); Žurn. èksper. teor. Fiz. **37**, 1464 (1959); JETP **10**, 1038 (1960).

[*393*] V. S. Barashenkov, E. K. Mihul, (will be published).

[*394*] Chou Kuang-chao, Žurn. èksper. teor. Fiz. **38**, 1015 (1960); JETP **11**, 730 (1960).

[*395*] P. S. Isaev, M. V. Sewerinski, Prepint of JINR D-550 (1960).

[*396*] B. W. Lee, Ph. D. Thesis; University of Pennsylvania; October, 1960.

[*397*] G. F. Chew, Preprint (1960); N. Cabibbo, R. Gatto, Phys. Rev. Lett. **4**, 313 (1960); L. M. Brown, F. Calogero, Phys. Rev. Lett. **4**, 315 (1960).

[*398*] G. F. Chew, S. Mandelstam, Phys. Rev. **119**, 467, 478 (1960).

[*399*] V. S. Barahsenkov, Preprint P-368 (1959) JINR.

[*400*] Z. Koba, Progr. Theor. Phys. **15**, 461 (1956).

[*401*] D. I. Blokhintsev, V. S. Barahsenkov, B. M. Barbashov, Uspekhi fiz. nauk **68**, 417 (1959).

[*402*] Riazuddin, Phys. Rev. **114**, 1184 (1959).

[*403*] Y. Yamaguchi, Rep. Padua-Venice Conf. 1957.

[*404*] S. Barshay, Phys. Rev. **109**, 2160 (1958); **110**, 743 (1958).

[*405*] M. Gell-Mann, Phys. Rev. **106**, 1296 (1957).

[*406*] D. D. Ivanenko, V. A. Lulka, V. A. Filimonov, Uspekhi fiz. nauk **68**, 663 (1959).

[*407*] A. S. Davydov, The Theory of Atomic Nucleus, Fizmatgiz 1958.

[*408*] Handbuch der Physik **39**, Springer, Berlin 1957.

[*409*] G. A. Bethe, P. Morrison, Elementary Nuclear Theory, J. Wiley New York; Chapman and Hall, London (1956).

[*410*] S. N. Biswas, V. Gupta, Nuclear Phys. **21**, 137 (1960).

[*411*] R. H. Dalitz, S. F. Tuan, Ann. of Phys. **8**, 100 (1959).

[*412*] I. Hamilton, W. S. Woolcock, Phys. Rev. **118**, 291 (1960).

[*413*] K. Symanzik, Nuovo Cimento **5**, 659 (1957); R. Arnowitt, G. Feldman, Phys. Rev. **108**, 144 (1957).

[*414*] V. B. Berestetzky, I. J. Pomeranchuk, Žurn. èksper. Fiz. **39**, 1078 (1960), JETP **12**, 752 (1961).

[*415*] F. Salzman, G. Salzman, Phys. Rev. **120**, 599 (1960).

[*416*] V. N. Gribov, Nuclear Phys. **22**, 249 (1961).

[417] I. J. Pomeranchuk, Žurn. èksper. teor. Fiz. **34**, 725 (1958); **7**, 499 (1958).

[418] N. N. Bogolubov, D. V. Shirkov, Introduction to the Theory of the Quantized Fields, Moskow, Gostekhisdat 1957.

[419] D. Amati, M. Fierz, V. Glaser, Phys. Rev. Lett. **4**, 89 (1960).

[420] J. u. M. Lomsadze, V. I. Lendnl, B. M. Earnest, Žurn. èksper. teor. Fiz. **39**, 803 (1961); JETP **12**, 803 (1961).

[421] V. S. Barashenkov, V. M. Maltsev, E. K. Mihul, Nuclear Phys. **13**, 583 (1959); V. S. Barashenkov, V. M. Maltsev, Nuclear Phys. **17**, 377 (1960).

[422] I. J. Pomeranchuk, Žurn. èksper. teor. Fiz. **30**, 423 (1956); JETP **3**, 306 (1956); L. B. Okun', I. J. Pomeranchuk, Žurn. èksper. teor. Fiz. **30**, 424 (1956); JETP **3**, 307 (1956); S. Z. Belenky, Žurn. èksper. teor. Fiz. **33**, 1248 (1957); JETP **6**, 960 (1958).

[423] D. I. Blokhintsev, Uspekhi fiz. nauk **61**, 137 (1957); Fortschr. Phys. **6**, 246 (1958) (in German); V. S. Barashenkov, B. M. Barbashov, E. I. Bubelev, Nuovo Cimento **7**, Suppl. **1**, 117 (1958).

[424] D. I. Blokhintsev, Uspekhi fiz. nauk. **62**, 381 (1957); D. I. Blokhintsev, Žurn. èksper. teor. Fiz. **35**, 254 (1958); JETP **8**, 174 (1959).

[425] M. A. Markov, Hyperonen and K-mesonen, Verlag der Wissenschaften, Berlin, 1960.

[426] V. S. Barashenkov, Sien Ding-Chang, Atomnaja Energia **9**, 489 (1960).

[427] M. A. Markov, The first article from [7].

[428] I. V. Polubarinov; see [7], p. 67 (1960).

[429] V. P. Silin, Žurn. èksper. teor. Fiz. **21**, 462 (1951).

[430] M. A. Markov, Proc. of the 10-th Intern. Conf. on High Energy Phys., S 4, 578 (1960), Rochester; I. M. Zheleznych, M. A. Markov, [7] page 17 (1960).

[431] D. I. Blokhintsev, Uspekhi fiz. nauk **69**, 3 (1959).

[432] D. H. Davis, R. D. Hill et al., Phys. Rev. Lett. **6**, 132 (1961).

[433] J. C. Caris, L. K. Goodwin et al., Phys. Rev. Lett. **6**, 159 (1961); Phys. Rev. **122**, 262 (1961).

[434] L. Bertanza, R. Carrara et al., Nuovo Cimento **19**, 467 (1961).

[435] V. S. Barashenkov, Huang Nai-nin, Žurn. èksper. teor. Fiz. **36**, 1319 (1959); JETP **9**, 935 (1959); V. S. Barashenkov, The Proceedings of the All-Union Inter-University Conference on the Quantum Field Theory and the Theory of Elementary Particles (1958).

[436] R. Hofstater, Ann. Rev. Nucl. Sci. **7**, 321 (1957).

[437] V. S. Barashenkov, B. M. Maltsev, E. K. Mihul, Prerint of JINR, D-597 (1960).

[438] L. van Rossum, Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.

[439] I. Button, P. Eberhard et al., Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.

[440] C. K. Hinrichs, E. P. Parker et al., Proc. of the 10-th Intern. Conf. on High Energy Phys., Rochester, 1960.

[441] S. Gartenhaus, Phys. Rev. **100**, 900 (1955); P. Signell, A. Marshak, Phys. Rev. **109**, 1229 (1958).

[442] Z. Koba, G. Takeda, Prog. Theor. Phys. **19**, 269 (1958).

[443] I. S. Ball, G. F. Chew, Phys. Rev. **109**, 1385 (1958).

[444] V. S. Barashenkov, Sien Ding-chang, Dokl. Akad. Nauk **134**, 65 (1960); V. S. Barashenkov, Fortschr. Phys. **9**, 42 (1961); G. Domokos, On the High Energy Behaviour of πN Elastic Scattering Amplitude (will be published).

[445] W. D. Walker, J. Crussard, Phys. Rev. **98**, 1416 (1955).

[446] R. I. Salukvadse, D. Nyagu, Preprint of JINR P-671 (1961).

[447] J. C. Caris, R. W. Kenney, V. Perez-Mendez, W. A. Perkins, Phys. Rev. **121**, 893 (1961).

[448] V. S. Barashenkov, G. Domokos (will be published).

[449] Ju. Volf, V. Zöllner (will be published).

[450] A. Barkow, B. Chamang et al, Phys. Rev. Lett. 6, 209 (1961).

[451] J. K. Kopp, A. M. Shapiro, R. I. Island, A. R. Erwin, Phys. Rev. Lett. 6, 327 (1961).

[452] A. S. Vovenko, B. A. Kulakov et al., Preprint D-721 (1961).

[453] A. S. Vovenko, B. A. Kulakov et al. (in print).

[454] C. K. Hinrichs, B. J. Moyer et al., Bull. Amer. Phys. Soc. 6, 29 (1961).

[455] W. Fickinger, E. Pickup et al., Bull. Amer. Phys. Soc. 6. 301 (1961).

[456] K. Miyake, K. F. Kinsey, D. E. Knapp, Bull. Amer. Phys. Soc. 6, 311 (1961).

[457] S. Goldhaber, G. Goldhaber, W. M. Powell, R. Silberberg, Phys. Rev. **121**, 1525 (1961).

Herausgeber: Prof. Dr. Rudolf Ritschl und Prof. Dr. Robert Rompe; Manuskripte sind zu richten an die Schriftleitung: II. Physikalisches Institut der Humboldt-Universität Berlin, Berlin N 4, Hessische Str. 2. Verlag: Akademie-Verlag GmbH, Berlin W 8, Leipziger Str. 3–4, Fernruf: 220441, Telex-Nr. 011773, Postscheckkonto: Berlin 35021. Die Zeitschrift „Fortschritte der Physik" erscheint monatlich; Bezugspreis dieses Heftes DM 6,–. Bestellnummer dieses Heftes: 1027/9/11. – Satz und Druck: Druckhaus „Maxim Gorki", Altenburg, Bez. Leipzig, Carl-von-Ossietzky-Str. 30–31. – Veröffentlicht unter der Lizenznummer ZLN 5028 des Ministeriums für Kultur. Printed in Germany.

Aus dem Inhalt der folgenden Hefte:

- **H. PAULY:** Streuversuche an Molekularstrahlen und zwischenmolekulare Kräfte
- **H. JOOS:** Zur Darstellungstheorie der inhomogenen Lorentzgruppe als Grundlage quantenmechanischer Kinematik
- **V. S. BARASHENKOV, H. J. KAISER:** Electric and Magnetic Polarizabilities of the Nucleons and Pions
- **A. I. ALEKSEEV:** Die Anwendung quantenfeldtheoretischer Methoden in der statistischen Physik (Uspechi fiz Nauk 73, 41, 1961)

F. R. GANTMACHER / M. G. KREIN

Oszillationsmatrizen, Oszillationskerne und kleine Schwingungen mechanischer Systeme

Übersetzung aus dem Russischen
Wissenschaftliche Bearbeitung der deutschen Ausgabe
Alfred Stöhr

(Mathematische Lehrbücher und Monographien, I. Abteilung, Band V)

1960. X, 359 Seiten — 3 Abbildungen — gr. 8° — Ganzleinen DM 42,—

In dem Werk wird die Anwendung der Vektor- und Matrizenrechnung sowie der linearen Integralgleichungen auf die Biegungen und Schwingungen linearer Kontinua behandelt (gespannte Fäden mit diskreten Massenpunkten sowie Saiten und Stäbe mit beliebiger Massenverteilung). Dabei auftretende Vorzeichenfragen werden eingehend diskutiert. Die zahlreichen Arbeiten der beiden Verfasser über dieses Thema sind übersichtlich zusammengefaßt. Da in einem Anfangskapitel auch die erforderlichen Sätze der Matrizentheorie hergeleitet werden, ist ungefähr die Hälfte des Werkes nur mit Kenntnis der Differential- und Integralrechnung lesbar. Die späteren Kapitel setzen einige Kenntnis über lineare Integralrechnung voraus.

AKADEMIE-VERLAG · BERLIN

BEITRÄGE AUS DER PLASMAPHYSIK

Herausgegeben von Robert Rompe und Max Steenbeck

ERSCHEINUNGSWEISE:

vierteljährlich 1 Heft mit 64 Seiten
im Format 16,7 × 24 cm zum Preise von 11,— DM je Heft
Bisher liegen vor: Band I, Heft 1—4

Die Zeitschrift veröffentlicht zusammenfassende Berichte und Stellungnahmen namhafter Autoren zu aktuellen Problemen der theoretischen und experimentellen Plasmaphysik. Ferner werden Originalmitteilungen in deutscher, englischer, russischer und französischer Sprache aufgenommen, die durch ihre Ergebnisse oder durch ihre Fragestellung von besonderer Bedeutung für die Plasmaphysik sind.

Aus dem Inhalt des 4. Heftes:

E. Hantzsche
Theorien des Kathodenfalls

F. Kümmel
Zustandsänderungen im isothermen Argon-Plasma

R. Rompe, S. Ullrich und H. Wolff
Zum Verhalten von Elektronen in Niederdruckplasmen

J. Wilhelm
Zur phänomenologischen Beschreibung eines diffusionsbestimmten Säulenplasmas

AKADEMIE-VERLAG · BERLIN